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AMS Tracker Thermal Control Subsystem

TTCS Commanding, Monitoring and Control

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Summary

The purpose of this document is to provide the reader a high level insight in how the TTCS is to be operated. In chapter 2 the layout and the functioning of the TTCS is described.
Attention is paid to explain the TTCS redundancy concept and the various redundant configurations that can be selected to constitute a fully functional cooling loop in the presence of equipment failures.

In chapter 3 the TTCS commanding, monitoring ad control concept is described.
The sub-sections of section 3.2 describe the low level monitoring and control of the TTCS firmware located in the TTCE. This includes control loops and healthguards.

The high level commanding and monitoring concept of the TTCS is described in section 3.3 and subsections. Described are:

- Explanation of the high level commanding operational procedures
    - Schedulable procedures
    - Non-schedulable procedures requiring ground monitoring
- Explanation of the high level TTCS loop commanding (write data types)
- High level TTCS monitoring and downlink budget

Two systems for TTCS commanding and monitoring are foreseen. For on-ground TTCS testing operations at CERN, ESTEC, and KSC a TTCS Ground Support Equipment is used. This is described in section 4.
The in-flight operations are done via a TTCS Ground Operations and Monitoring System. described in section 5 (to be written). An explanation of the JMDC command list is given in chapter 6.

As the telemetry downlink has limited bandwidth, it is desirable to have the possibility for "autonomous on-board" of the non-schedulable TTCS start-up related procedures, under control of on-board software implemented in the JMDC. Chapter 8 therefore presents some TTCS operational rules and procedures and identified non-schedulable operational procedures associated with the start-up of the TTCS. The defined procedures can be implemented (at least partially) in software and executed "semi-autonomously on board" by the JMDC.
The current baseline for routine TTCS in-flight operations is to use the JMDC command list in view of the limited required bandwith of only 183 bits/second.

Chapter 7 decribes high level health-guards to be implemented in the JMDC. The purpose of the health-guards is to raise alarms and -if possible- to take action to protect the Tracker or TTCS for malfunctioning. Three healthguards are foreseen:

- Tracker electronics high and low temperature healthguard
- Radiators freezing healthguard requiring action on 120 V PDS controlled heaters
- JMDC-TTCS communication outage healthguard

Note.
This document is not applicable for safety. TTCS is inherently safe in all space environmental conditions while assuming the TTCE electronics is in the most unfavourable possible state.
The health-guards described are only for subsystem health and warn the operator of unfavourable situations for TTCS or Tracker.

Note.
Information on Write and Read Data Types and TTCE firmware was taken from Ref. 20, a copy of which has been added in the appendix at the end of this document.

Contents

(97 pages in total)

1 Introduction

1.1 Purpose and scope of this document

The purpose of this document is to provide the reader a high level insight in how the TTCS is to be operated.

In chapter 2 the layout and the functioning of the TTCS is described.

Attention is paid to explain the TTCS redundancy concept and the various redundant configurations that can be selected to constitute a fully functional cooling loop in the presence of equipment failures.

The TTCS can be started up and operated in different configurations, thanks to its redundancy.

- TTCE-A powered on, controlling Primary Loop using "a" components
- TTCE-A powered on, controlling Secondary Loop using "a" components
- TTCE-B powered on, controlling Primary Loop using "b" components
- TTCE-B powered on, controlling Secondary Loop using "b" components

So, first it must be selected which TTCE (A or B)is powered-on, next it is selected which Loop (Primary or Secondary) is to be started-up.

In chapter 3 the TTCS commanding, monitoring ad control concept is described.

The sub-sections of section 3.2 describe the low level monitoring and control of the TTCS.

At low level the TTCS is automatically controlled by (FPGA) firmware located in the TTCE. The firmware provides low-level control functions, i.e. on-off control of heaters and PI control of the accumulator temperature. Furthermore, the firmware provides low level monitoring of the TTCS in the form of so-called health-guards, which monitor the TTCS functioning and raise alarms in case the TTCS does not operate correctly.

The sub-sections of section 3.3 describe the high level commanding and monitoring concept of the TTCS.

The high level TTCS (in-flight) operations are done via a TTCS Ground Operations and Monitoring System. For on-ground TTCS testing operations at CERN, ESTEC, and KSC a TTCS Ground Support Equipment is used.

At high level the TTCS is operated by a TTCS operator by sending commands (called Write Data Types) to the TTCE. These commands concern for example setpoint changes for the accumulator temperatures control loop, setting of control parameter values, etc..

To this end the appropriate Write Data Type must be configured with the correct bits settings for the intended operations.

The required different bits settings for the Write Data Types, required to perform operations such as enabling 28Vsupply power, enabling/disabling control loops, setting accu setpoint value, setting loop control parameter values, , etc., are not presented as a description at this level is not available to NLR.

It is noted that closed loop operation of each control loop can be disabled/enabled and heaters may be operated ON/OFF "manually" via sending of the appropriate Write Data Type containing the correct bits settings for the intended operation.

In-flight the commands are sent to the JMDC, which further forwards them to the TTCE.
For on-ground testing operations the TTCS Ground Support Equipment may send the commands directly to the TTCE, circumventing the JMDC.

At high level the TTCS is monitored via telemetry which is to be acquired by sending commands called Read Data Types to the TTCE. The TTCE responds to a single Read Data Type by returning a data set, associated with that Read Data Type.
A continuous stream of telemetry data can be obtained by loading a table of Read Data Types in a Data Polling Table in the JMDC. The JMDC cyclically executes the Data Polling Table and sends the Read Data Types to the TTCE, which in its turn responds with the requested data sets.
The JMDC receives the return data from the TTCE and processes the data for further relay to the TTCS Ground Operations and Monitoring System.
The Write Data Types x07, x08, x09, and x0A which are important for high level commanding of the TTCS are briefly described.
Some extra attention is paid to a table listing the power-on default values of the TTCS loop control parameters. and the Read- and Write Data Type which are associated with the setting and reading of the TTCS loop control parameters values.
It is noted that the power-on default values of the accumulator control loop parameters K1, K2, K3, range, and iband are not suited for operational use
In section 3.3.2.5 a table with accumulator control loop parameters and their values to be used is presented.
These values have to be up-loaded into the TTCE as part of the TTCS loop start-up procedure, as the power-on default values are not suited.
Furthermore it is noted that also the power-on default setpoints of the pre-heaters are not suited for operational use. The correct values must be uploaded into the TTCE, as part of the TTCS loop start-up procedure.

In section 3.3.3.2 the Read Data Types which are associated with the most important data sets to be retrieved from the TTCS for routine monitoring are briefly presented and a required downlink budget is calculated.

As has been said above, the TTCS in-flight operations are done using a TTCS Ground Operations and Monitoring System, whereas for on-ground TTCS testing operations at CERN, ESTEC, and KSC a TTCS Ground Support Equipment (TTCS GSE) is used.
Chapter 4 briefly presents the user interfaces of the TTCS GSE.
Chapter 5 (to be written) describes the TTCS Ground Operations and Monitoring system.

The JMDC plays a central role in the in-flight monitoring and operation of the TTCS.
Firstly, a number of health-guards are to be implemented in the JMDC software. The purpose of the health-guards is to raise alarms and -if possible- to take action to protect the Tracker for malfunctioning of the TTCS or in case of communication loss between TTCE and JMDC.
The high level health-guards to be implemented in the JMDC are described in chapter 7.

Secondly, the JMDC plays a role in the in-flight operation of the TTCS.
In order to prevent errors in the in-flight operation of the TTCS, the operations are organized via operational procedures which are written and verified in advance.
If the TTCS is routinely operational, the normal operations will be mainly limited to the occasional sending of commands to the TTCE to adapt the accumulator setpoint to the anticipated orbital environment. Three main orbital environments are distinguished: cold orbit, normal orbit, and hot orbit. Each orbit type has its preferred accumulator setpoint.
The orbit types can be foreseen in advance and hence the associated operational commands (Write Data Types) can up-loaded in advance in the so-called command list in the JMDC. The commands in the command list are executed by the JMDC (send to the TTCE) at the time of their time tag (time tagged execution).
This type of operational procedure, where the Write Data Type(s) can be loaded in advance in the command table in the JMDC for immediate or time tagged execution, is called a schedulable procedure.
The current baseline for routine TTCS in-flight operations is to use the JMDC command list.

While the TTCS is routinely operational, it is monitored via the execution of a Data Polling table associated with routine operation. The cyclical execution of the routine TTCS Data Polling Table causes a low data rate TTCS telemetry stream for monitoring. The foreseen routine monitoring data sets and polling rate are specified in section 3.3.3.2.

The procedures foreseen for start-up of the TTCS are not well schedulable via the JMDC command list.
A TTCE (-A or -B) can -under all circumstances- be powered-on, without endangering the TTCS.
After powering-on of a TTCE, a TTCS loop configuration (Primary A or B or Secondary A or B) can be started-up further via sending Write Data Type requests to the TTCS.
Start-up of the TTCS does require continuous monitoring of TTCS on-board statuses (mainly temperatures) by the TTCS operator and verification of intermediate decision criteria, as it has to be checked that certain measured TTCS temperatures and statuses satisfy well defined criteria, before the next commands may be sent.
The required monitoring data during the process will put some additional burden on the required downlink budget. As the telemetry downlink has limited bandwidth, it is desirable to have the possibility for "autonomous on-board" of the non-schedulable TTCS start-up related procedures, under control of on-board software implemented in the JMDC. This would alleviate the TTCS down-link data rate.

Chapter 8 presents some TTCS operational rules and procedures
Section 8.2 present some TTCS operations know-how and operational rules which must be taken into account.
Sections 8.3.1 to 8.4 present the currently identified non-schedulable operational procedures associated with the start-up of the TTCS.

The defined procedures may be executed "manually" from the ground, but could also be implemented (at least partially) in software and executed "semi-autonomously on board" by the JMDC.
The term semi-autonomously is used as it is anticipated that the JMDC can not perform all operations required for start-up.
One operation that has to be performed in the sequence of commands for TTCS start-up and that probably can not be performed autonomously by the JMDC is the powering-on of the radiator health heaters by the PDS. It is currently unknown if this operation can be performed autonomously by the JMDC.
Another operation that has to be performed in the sequence of commands for TTCS start-up is the switching-on of the Tracker. It is anticipated that this can not be done by the JMDC.
So the "semi-autonomous start-up of the TTCS by the JMDC is to be interrupted with commands from ground to power-on the radiator health heaters and to switch-on the Tracker. This does require some data exchange of the JMDC with the ground about the execution status of the start-up procedure.

The term "manual" implies in this context commanding of the TTCS via commands directly issued from the ground, and monitoring statuses and temperatures on the ground, such that the (start-up) procedure can be followed.

The term "on-board" implies implementation in software in the JMDC. In this situation the JMDC plays the role of the TTCS operator on the ground, taking decisions whether to continue or to abort the start-up procedure based on monitoring TTCS telemetry acquired by the execution of a TTCS Data Polling Table associated with TTCS start-up.

It is emphasized, that the TTCS operator still has the option to execute the procedures associated with TTCS start-up "manually" at the ground, or to command the activation of the "autonomous start-up" in the JMDC.

Chapter 8 presents some TTCS operational rules, and the currently identified procedures associated with start-up.
Section 8.2 present some TTCS operations know-how and operational rules and which must be taken into account.
Sections 8.3.1 to 8.4 present the currently identified non-schedulable operational procedures associated with the start-up of the TTCS, which are amenable for implementation in the JMDC.

Information on Write and Read Data Types and TTCE firmware was taken from Ref. 20, a copy of which has been added in the appendix at the end of this document.

Note.
This document is not applicable for safety.
TTCS is inherently safe in all space environmental conditions while assuming the TTCE electronics is in the most unfavourable possible state.
The health-guards described are only for subsystem health and warn the operator of unfavourable situations for TTCS or Tracker.

1.2 Reference documents

Ref. 1	Combined proposal Development of the Tracker Thermal Control System of the Alpha Magnetic Spectrometer, SYSU/NLR/INFN, J. van Es, B. Oving, R. van Benthem, July 2004.	NLR-ASSP-2004-021 Issue 1
Ref. 2	TTCS Box Temperature Requirements	AMSTR-NLR-TN-31 Issue02
Ref. 3	TTCS Thermal Analysis Results	TTCS-SYSU-SIMU-PR-003 Issue 1.0
Ref. 4	AMS-02 Tracker Thermal Control System (TTCS) Cold Environment Temperatures	ESCG-4470-06-TEAN-DOC-0032
Ref. 5	TTCS Test Report for Micro-g 2nd Loop Performance test	AMSTR-SYSU-TRP-04-iss1.0
Ref. 6	TTCS Test Report for Micro-g 1st Loop Performance test	AMSTR-SYSU-TRP-05-iss1.0
Ref. 7	TTCS EM Test Report for both 1st and 2nd Loop in 3D lay-out	AMSTR-SYSU-TRP-010-iss1.0
Ref. 8	TTCS QM Test Report for 2nd Micro-g Loop Performance Test	AMSTR-SYSU-TRP-016-iss1.0
Ref. 9	TTCB Primary Drawing package	ET5998-06 Release 15-09-2009
Ref. 10	TTCB Secondary Drawing package	ET5998-08 Release 15-09-2009
Ref. 11	Revised requirements for the pumps of the AMS Tracker Thermal Control System (TTCS)	AMSTR-NL-TN-010 Issue 04
Ref. 12	PDT pump proposal, TP-5059-2, “AMS Tracker Thermal Control System Pump”	TP-5059-2, Revision B, 03-SEP-2004
Ref. 13	TTCS Accumulator Specification	AMSTR-NLR-TN-18-Issue03
Ref. 14	Design of TTCS Accumulator	AMS02-CAST-TTCS-ACC-DR-002
Ref. 15	TTCS Heat Exchanger Design	AMSTR-NLR-TN-053 Issue 1.0
Ref. 16	TTCS Radiator & Condenser Simulation Results	AMSTR-SYSU-SIMU-PR-005-1.0
Ref. 17	TTCE software user requirements document	AMSTR-NLR-TN-034 Issue 3
Ref. 18	TTCS Component list	ComponentsList_16_09_V51.xls
Ref. 19	TTCS System design Description	AMSTR-NLR-TN-05-Issue03 NLR Contract Report CR-2006-014

Ref. 20	TTCE_Data_Type3.txt by V. Koutsenko attached as Appendix II in this document	6 February 2008
Ref. 21	AMS02 Interface Control Document Electrical and data	AMSTR-NLR-TN-24-Issue 4.0

2 TTCS Description

2.1 TTCS Primary and Secondary cooling loop layout

The system lay-out for the Primary Loop is shown in Figure 2-1. The loop lay-out for the Secondary Loop is shown in Figure 2-2. The task of the TTCS loop is to transport heat dissipated by the Tracker electronics to the Tracker radiators, which radiate the transported heat to cold deep space.

For reliability reasons, two redundant loops are implemented. The Secondary Loop is identical to the Primary Loop, except that the tube length to the inlet of the evaporator is slightly larger for the Secondary Loop. By following the loop routing, starting from the pre-heaters, in Figure 2-1 and Figure 2-2 the loop operation is explained. At the pre-heaters the CO_2 working fluid temperature is lifted to the saturation temperature. The working fluid enters the evaporator with a vapour quality slightly above zero, ensuring a uniform evaporation temperature along the complete evaporator. Due to the widely dispersed Tracker front end electronics the evaporator consists of two parallel branches collecting the heat at the bottom and top side of the Tracker electronics planes. At an overall CO_2 mass flow of 2 g/s the mean vapour quality at the outlet of the evaporators is approximately 30%.

At the connection point of the outlets of the two evaporator branches, the two-phase flow of both branches is mixed and led through the heat exchanger where heat is exchanged with the incoming sub-cooled liquid. Behind the heat exchanger the two-phase line (red) is split. One branch leads to the condensers mounted to the radiator at the RAM (bow) side and the other is lead to the condensers mounted to the radiator at the WAKE (stern) side of the AMS spacecraft. At the radiators the heat is rejected to space.

After the mixing point in the return of the two radiator branches, the sub-cooled fluid passes the accumulator connection. By controlling the accumulator temperature the evaporator set-point temperature is controlled. The accumulator temperature is controlled by using Peltier elements (TECs) for cooling and heaters for heating. The evaporation temperature setpoint can be varied, in order to be able to avoid extreme sub-cooling of the liquid entering the pump, and to avoid operation at liquid temperature close to saturation at the inlet of the pump. A certain amount of sub-cooling (currently chosen default 5ºC) is required to avoid cavitation at the pump. After the pump the sub-cooled fluid is warmed up in the heat exchanger before it enters again the pre-heater section.

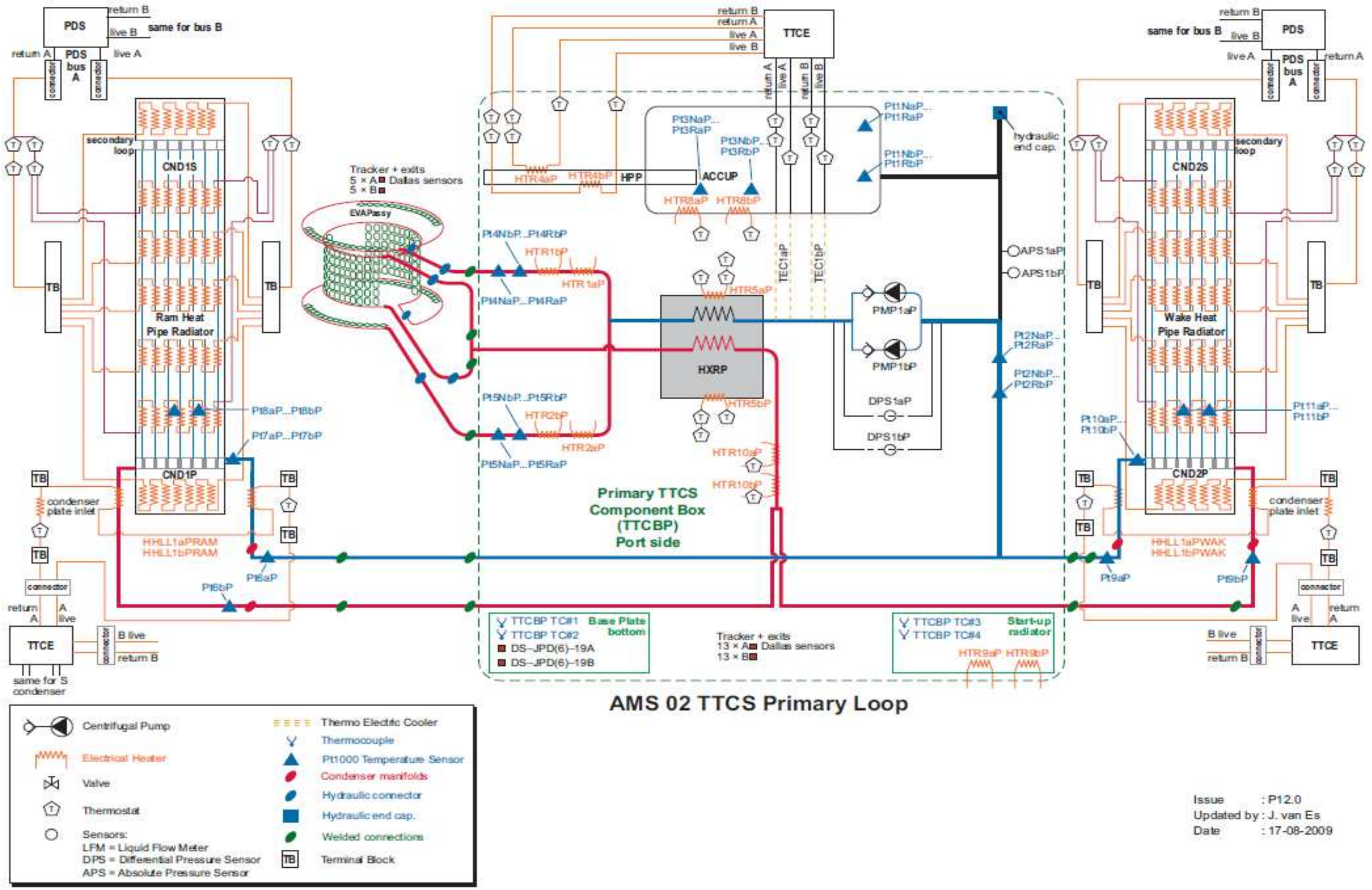


Figure 2-1: Schematic of the Tracker Thermal Control System Primary Loop

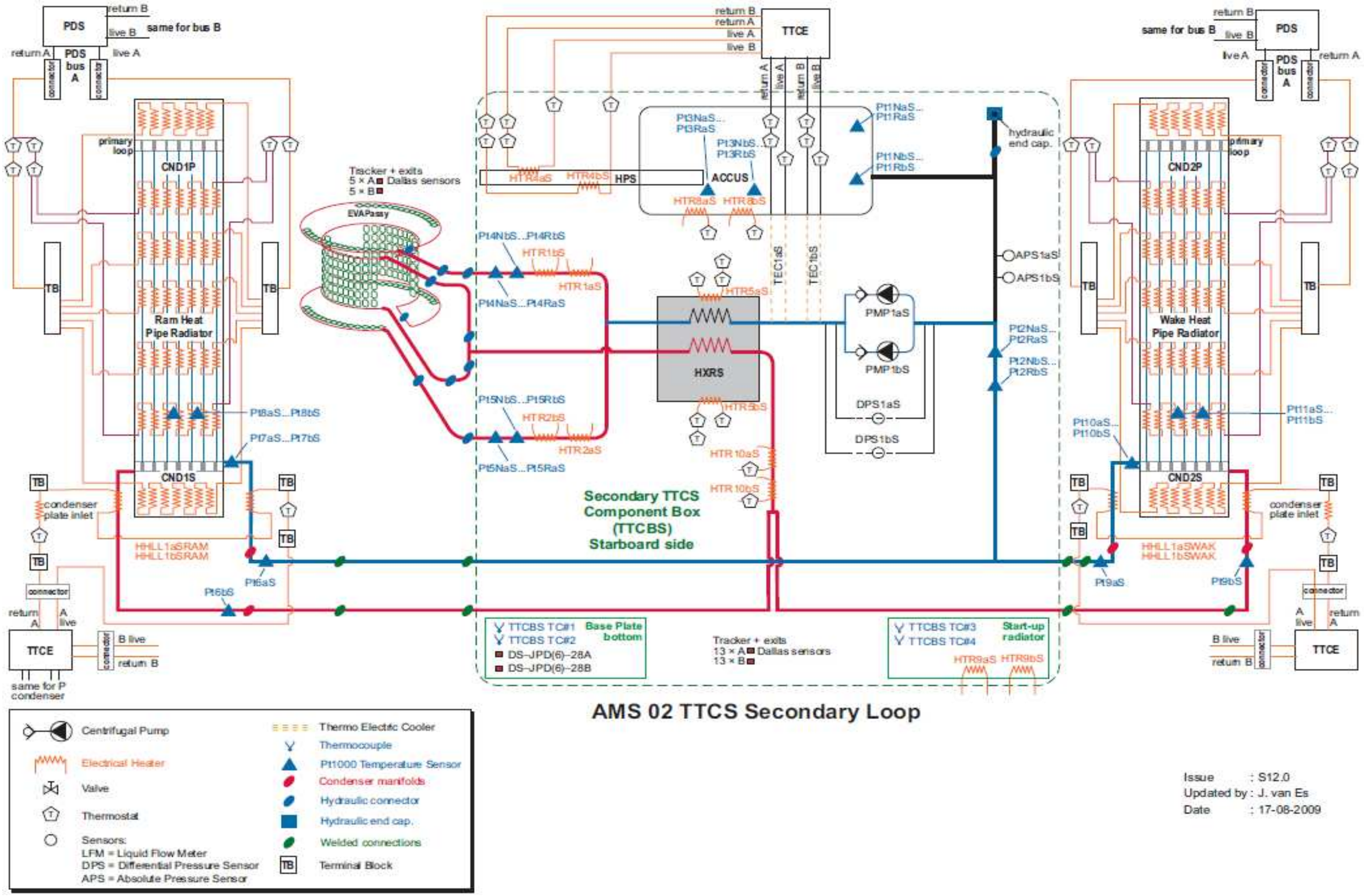


Figure 2-2: Schematic of the Secondary Loop

2.2 TTCS loops redundancy concept

The AMS overall philosophy is **the avoidance of any single-point of failure**. The TTCS subsystem is therefore completely redundant. **Two complete independent loops are fully equipped to fulfil the thermal control task** for the Tracker electronics. In principle one subsystem is hot and the other is in cold standby (i.e. the subsystem will not be operating at the same time)

The philosophy is further that also **no single-point of failure is present in one of the two systems**. All critical mechanical components in the separate loops are therefore also redundant. A list of redundant components is given in Table 2-1.

Component	Redundancy per loop (# per loop)
Pump	2
Accumulator	1
Accumulator Peltier elements (TECs)	2
Accumulator heaters	2
Heat Exchanger	1
Evaporator	1
Condensers	1
Absolute Pressure Sensors	2
Differential Pressure Sensor	2
Pre-heaters	2
Start-up heaters	2
Dallas Temperature Sensors	2
Pt1000 Temperature Sensors	3 or 2**
Cold orbit heaters	2
Liquid line health heaters	2
Tracker radiator heaters***	2 (connected to PDS A-side and to PDS B-side)
TTCE including:	**2**
TTEP	2
TTEC	2
TTPP (A/B) A and B both on one board	2 (but one mechanical connector) No control-Pt1000's are connected to this board.
TTBP (A/B) A and B both on one board	2
Redundancy interfacing systems	
CAN-bus	2
JMDC	4

Table 2-1 Component redundancy

*** The Pt1000's used for control are triple redundant the monitoring Pt1000's are redundant.*
****The radiators survival heaters are not part of the TTCS-system but are incorporated for completeness.*

2.3 TTCS Electronics redundancy concept

The TTCE electronics are also completely redundant and divided in an A and B electronics block. A block diagram is shown in Figure 2-3.

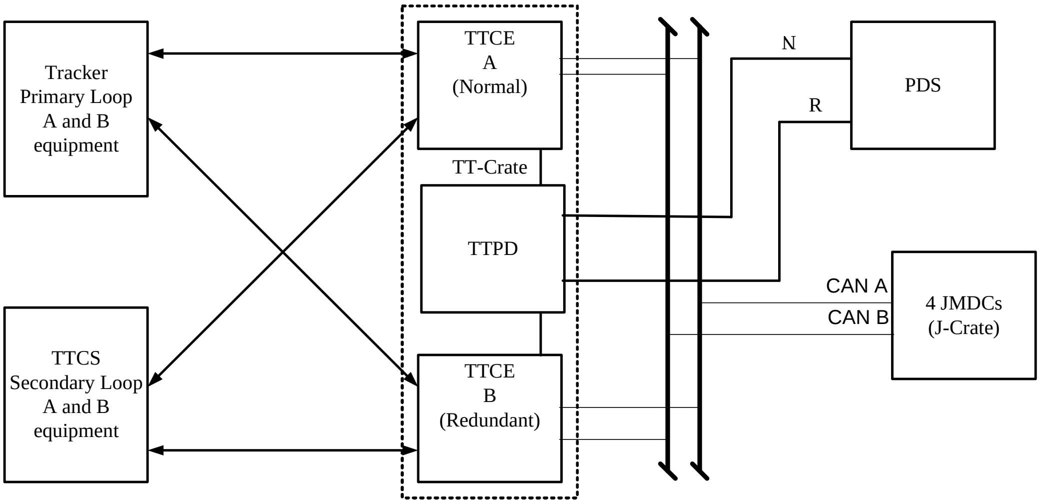


Figure 2-3: TTCS Block Diagram

So, all electrical components are redundant in as well the Primary as the Secondary Loop. One set of equipment (designated the "A" equipment) of a loop is attached to Electronics A and the redundant set of equipment (designated the B components) of the same loop is connected to Electronics B. This is more clearly illustrated in Figure 2-4 below

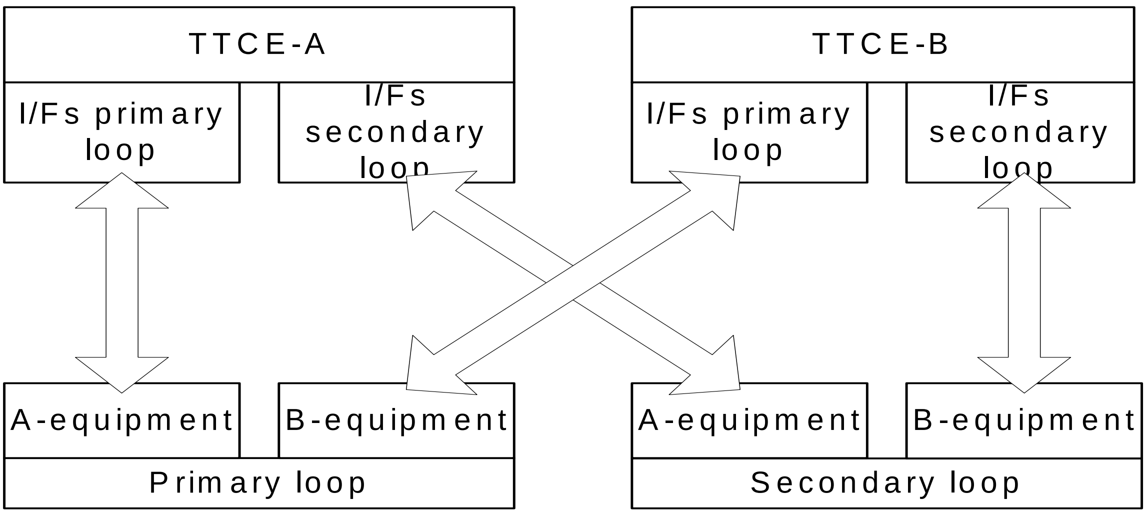


Figure 2-4 Operation of Primary or Secondary Loop using A or B equipment.

2.4 TTCE Electrical Interfaces with cooling loop equipment

The electrical interfaces of the TTCEs (A and B) with their associated Primary and Secondary Loop A and B equipment shown above are further detailed at board level in **Error! Reference source not found.**.

All details on the electrical interfaces are summarised in the AMS02 TTCE Interface Control Document, Ref. 21.

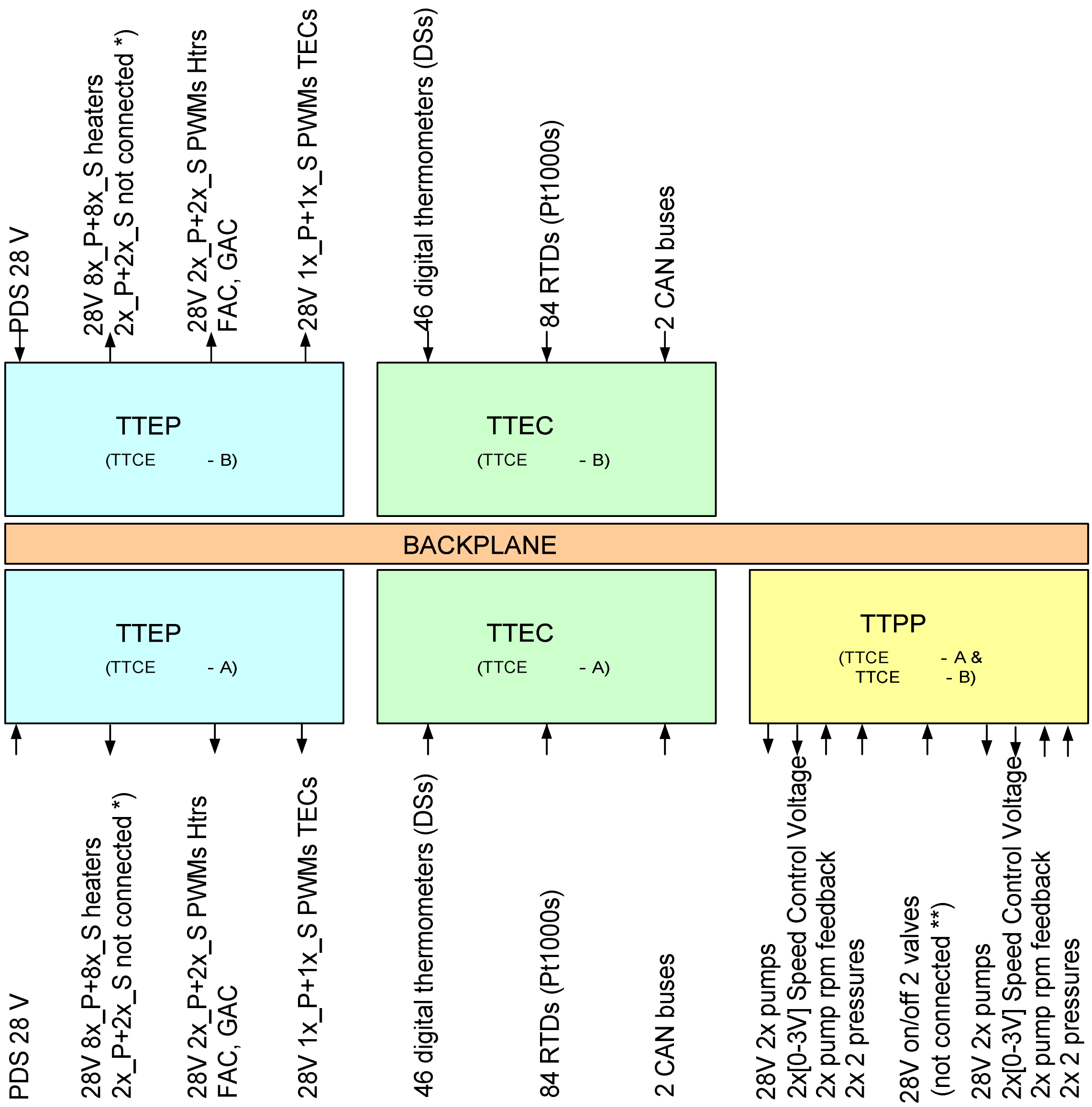


Figure 2-5TTCE electrical interfaces with cooling loop equipment

*) Not connected heaters are accu emergency (FAE) and ground accumulator test emergency (GAE) heaters, which have been combined with the FAC respectively GAC control heaters.
**) Valves were deleted from the design after successful breadboard tests, showing robust condenser operation.

2.5 TTCS Operational Configurations

2.5.1 Normal operational TTCS configurations

From the description of the redundancy concept in section 2.2 above it follows that there are different redundant configurations in which a cooling loop can be operated

1. TTCE-A powered on, controlling Primary Loop using "A" equipment
2. TTCE-A powered on, controlling Secondary Loop using "A" equipment
3. TTCE-B powered on, controlling Primary Loop using "B" equipment
4. TTCE-B powered on, controlling Secondary Loop using "B" equipment

This is illustrated in Figure 2-3 and Figure 2-4 above.

2.5.2 Special operational TTCS configurations

To allow for the maximum use of redundancy of all critical components it has been decided that it should be possible to operate A and B electronics simultaneously, leading to the following special configurations.

1. Special configuration: Simultaneous Primary and Secondary Loop operation with TTCE-A or TTCE-B

This special case is required to check on a regular basis the health of the pump of the Secondary Loop.
In this special case the Primary Loop is fully operational and the Tracker is ON.
It is noted that in order to prevent boiling in the secondary loop for this special case it is required to enable the accumulator control of the Secondary Loop and to run it at a higher setpoint than the Primary Loop.
The ON/OFF control loops should not be enabled in this special case.

2. Special configuration: Primary Loop operation with TTCE-A and TTCE-B operating simultaneously.
3. Special configuration: Secondary Loop operation with TTCE-A and TTCE-B operating simultaneously.

These latter two special cases shall be possible in order to be able to use the redundancy of the TTCS to the full.

Firstly, in this special case it is possible to operate a cooling loop with one TTCE while redundantly monitoring the loop with the other TTCE. For example the Primary Loop could be operated with TTCE-A, while the TTTCE-B could be redundantly monitoring the Primary Loop. This would provide for cross-checking of -A and –B equipment, (except the pumps).
Furthermore, the health of the redundant pump could be checked, by starting up the redundant (parallel) pump.
The same example holds for the Secondary Loop.

Secondly, in this configuration it is possible to use the TEC-A and TEC-B simultaneously.
The purpose of the TECs is to provide cooling to the accumulator, by dumping heat from the accumulator (the "cold side" of the TECs) into the sub-cooled part of the loop (the "hot side" of the TECs). The current cooling performance of the TECs is severly hampered, due to the chosen mounting configuration, where the TEC-A and TEC-B are mechanically connected to and mounted parallel to each other. This leads to a short circuit heat conduction path from the hot side to the cold side of the TEC: if TEC-A is activated, heat withdrawn from the accumulator leaks back to the accumulator from the hot side of A via the TEC-B. Likewise, if TEC-B is operated heat leaks back via TEC-A.
Simultaneous activation of TEC-A and TEC-B alleviates this problem.
This has been shown to work under "manual" ON/OFF control of the TEC.
However, it is questionable whether this can be done under closed loop control.

Thirdly, as it is possible to enable/disable the various control loops individually and enable/disable alarms actions individually, in theory it is possible to have some control loops being executed by TTCE-A while others are executed by TTCE-B. One important health-guard to be dealt with in this situation is the Low Pump Speed health-guard.
It is to be born in mind that in the TTCE which does not control the active pump the Low Pump Speed alarm will be active, disabling the 28V power to heaters and TEC, so the LPS alarm action is to be disabled in the pertinent TTCE.

It is emphasized, that this type of mixed operation using TTCE A and TTCE-B has not been exercised yet and should only be tried-out under strict ground command and monitoring, only in case there is no other alternative.

3 TTCS Command, Monitoring and Control concept

3.1 Introduction into TTCS command, monitoring and control functions

In this section the commanding, monitoring and control concept of the AMS02 Tracker Thermal Control System (TTCS) is described.

The TTCS operational system comprises:

- **TTCS Ground Segment (TTCS-GS)** including the TTCS Ground Monitoring & Control System
- **TTCS Space Segment (TTCS-SS)** including a limited amount of TTCS related software located in the JDMC, and the TTCE firmware and associated TTCS loop components.

An overview of the TTCS Space Segment and the TTCS Ground M&C System architecture is given in Figure 3-1 below. The TTCS Space Segment comprises the TTCE A and B, the Primary Loop and its A and B equipment, the Secondary Loop and its A and B equipment, and the TTCS related software running in the JMDC.

The current baseline division of functions for TTCS commanding, monitoring and control is:

High level command and monitoring functions located on ground in the TTCS-GS:

- High level command of the TTCS-SS via sending of telecommands (Write Data Types request) to the TTCS-SS,
- High level monitoring of the TTCS-SS operation via telemetry acquired from the TTCE by the JMDC via the execution of Data Polling Tables, sending Read Data Types requests to the TTCE, which responds with the associated response data.

High level command and monitoring functions located in JMDC:

- telecommand and monitoring data I/F functions with TTCEs,
- functions for (semi-) autonomous execution of start-up procedures of the TTCS and associated monitoring..

High level health-guards located in the JMDC

Health-guards are applied at low level in the TTCE (see section 3.2.3) and at high level in the JMDC.

The high level health-guards in the JMDC are required to protect the Tracker against malfunctioning of the TTCS.

It is noted that high level health-guards have been defined by NLR, but have not yet been implemented in the JMDC.

Low level control and monitoring functions located in the TTCEs: see section 3.2

Low level control of the TTCS loops the TTCE firmware, which implement:

- TTCS control loops,
- TTCS health-guards (alarms),

- Read/Write Data Types interface (via CAN bus) functions for the executions of Read and Write Data types, i.e. telemetry and telecommand functions.

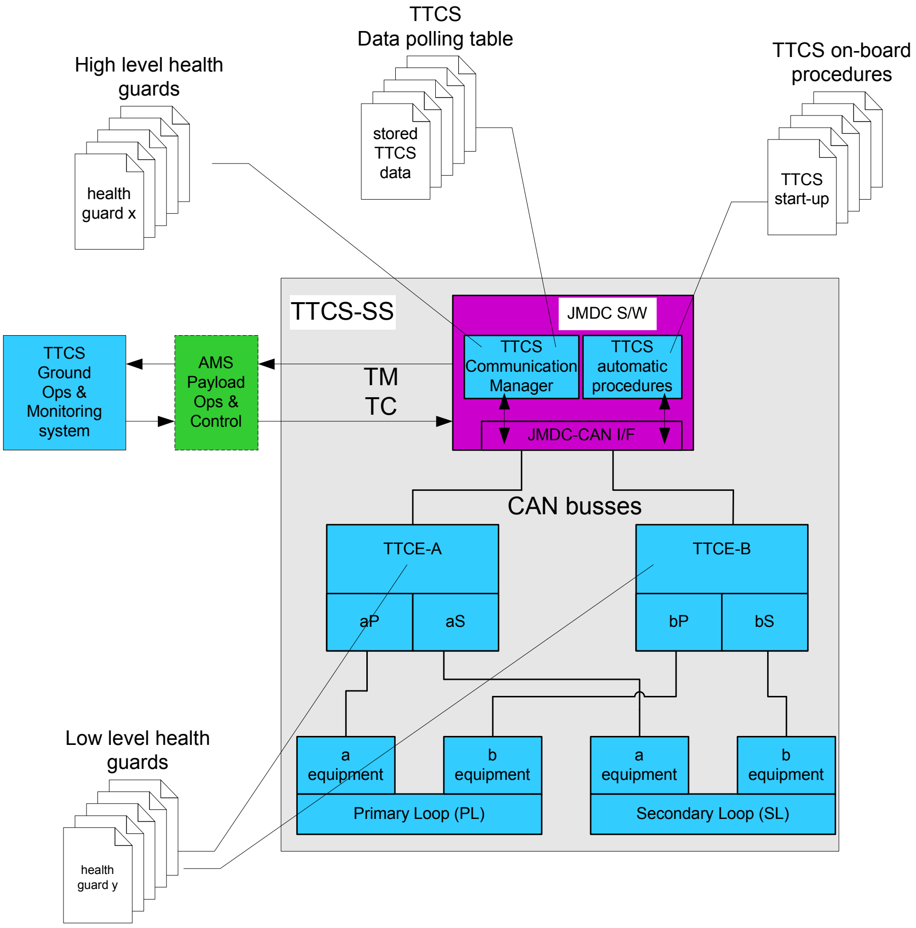


Figure 3-1: Overview of TTCS Space Segment and TTCS Ground M&C System.

3.2 Low level TTCE located TTCS control and monitoring functions

3.2.1 Low level TTCE located TTCS control loops

The low level loop controls in the TTCE and their acronyms are

1. on/off heater control loops:
   - Condenser liquid lines health heaters RAM: LLR
   - Condenser liquid lines health heaters WAKE: LLW
   - Pre-heaters 1 and 2 control loops: PR1 and PR2
   - Start-up heater control loop: SUP
   - Cold orbit heater: COR

Each heater on/off control loop can be ENABLED/DISABLED by sending Write Data Type 0x0A, (carrying the bit settings required for this purpose) to the TTCE.

Each heater can also be operated "manually", where the heater is set ON/OFF by sending Write Data Type x07 (carrying the bit settings required for this purpose) to the TTCE.

2. Accumulator PI control
   - Accumulator PI control loop comprises a heater for heating (FAC) and Peltier element (TEC) for cooling. The flight accumulator control (FAC) heater is actuated by a filtered PWM output (0 ... + 28 V) for heating. The TECs are actuated by a filtered PWM output (0 … + 28 V) for cooling. Furthermore the accumulator is equipped with ground test heater (GAC).

The accumulator PI control loop can be PI_ENABLED/PI_DISABLED by sending Write Data Type 0x0A, (carrying the bit settings required for this purpose) to the TTCE.

The accumulator heaters/TECS PWMs can also be operated manually, i.e. directly by sending Write Data Type 0x09, (carrying the bit settings required for this purpose) to the TTCE.
request to the TTCE.

It is to be born in mind that the redundancy concept of the TTCS -and the resulting different operational configurations- fully apply to all control loops and their operation.

For ground testing purposes a Ground Accumulator Control (GAC) heater has been incorporated.

The initially planned Ground Accumulator Emergency (GAE) heater and Flight Accumulator Emergency (FAE) heater have not been incorporated as separate heaters, but have been added to the GAC respectively the FAC.

3.2.2 Pump speed control

At low level, the pump speed is feedback-controlled by the pump's own local speed-control electronics, located at the pump. The pump controller outputs a speed monitoring signal which is read by the TTCE.
At high level, the pump speed setpoint can be changed by sending a Write Data Type x08 request (carrying the bit settings required for this purpose) to the TTCE, which in its turns provides a settable analogue voltage to the pump controller.

It is to be borne in mind that the redundancy concept of the TTCS -and the resulting different operational configurations- fully apply to the pumps and their operation.

3.2.3 Low level TTCE monitoring by TTCE located health-guards

3.2.3.1 Introduction

Health-guards are present at low-level in the TTCE and at high-level in the JMDC.

Note:

Although high-level health-guard functions in the JMDC have been proposed and described by NLR, see chapter 7, they are still yet to be developed.

Below the low level health-guards/alarms implemented in the TTCE are discussed.

3.2.3.2 Low level Health-guards and their alarm actions implemented in the TTCE

The following low level health-guards have been implemented in the TTCE:

Health-guard/ alarm nr	Alarm acronym	Full Health-guard/alarm descriptive name
0	CAV_alarm	Cavitation margin health-guard
1	TRK_alarm	Working temperature out of Tracker range health-guard
2	PR1_alarm	Preheater 1 temperature too high health-guard
3	PR2_alarm	Preheater 2 temperature too high health-guard
4	LLR_alarm	Condenser lines health heaters RAM temperature too high health-guard
5	LLW_alarm	Condenser lines health heaters WAKE temperature too high health-guard
6	LPS_alarm	Low pump speed health-guard
7	GAC_alarm	Accu ground test accu heaters temperatures too High health-guard

Table 3-1: Table of low-level health-guards located in the TTCE

If a health-guard is triggered it raises an alarm flag and can execute an alarm action. The health-guards run at the TTCE cycle rate and can not be disabled, so in alarm situations the health-guards' alarm bits will always be set, however a health-guard's alarm actions can be ENABLED/DISABLED.

Below the health-guards and their operation are described in more detail.

CAV_alarm: Health-guard: Cavitation margin health-guard

Hazard

The temperature of the subcooled return liquid at the pump inlet may come close to the saturation temperature belonging to the currently set accumulator pressure/temperature, such that, if the temperature of the return liquid would further increase, insufficient sub-cooling at the pump inlet would exist and cavitation at the pump inlet would occur.

CAV_alarm flag:

The CAV_alarm bit is set to Not_OK if difference between the accumulator setpoint and the pump inlet temperature (the sub-cooling margin) is less than the cavitation margin, i.e. if:

Set_point – Pt01 < CAV_margin.

CAV_alarm action:

The health-guard action execution increases the accumulator setpoint. The setpoint increase is coupled to the measured pump inlet temperature. The setpoint is increased such that the cavitation margin is preserved: i.e. the setpoint is set 5 ºC above the measured pump inlet temperature. The setpoint may be increased to a maximum of 25 ºC.

Furthermore the health-guard action switches off heaters: LLW, LLR, PR1, PR2, COR, SUP.

Note:

If the CAV_alarm is OK again, the accumulator setpoint returns to its original value again.

During alarm situations this may cause jitter of the accumulator setpoint between the increased setpoint and the original setpoint.

TRK_alarm: Health-guard: Working temperature out of Tracker range:

Hazard

1. At the time of TTCS start-up the liquid flowing through the evaporators may be too cold for the tracker. If this is the case the start-up heaters and the pre-heater on/off control loops will be active. This mechanism might fail for some reason or initially might not immediately be capable to achieve the minimum survival temperature of the Tracker Electronics (-20 °C).
2. The accumulator temperature may become too high e.g. because of an accumulator control error, leading to a too high evaporator temperature and higher than the upper Tracker Electronics operational temperature (+ 25 °C).

TRK_alarm flag:

The TRK_alarm bit will is set Not_Ok if the evaporator temperatures:

+20ºC < Pt04 < -20ºC or

+20ºC < Pt05 < -20ºC

It is noted that the upper alarm temperature has been chosen slightly below the upper operational temperature of the Tracker.

TRK_alarm action:

No low level alarm action is coupled to this alarm. The alarm bit may be used at higher level (JDMC).

PR1_alarm: Health-guard: Pre-heater 1 temperature too high

Hazard

The temperature at the pre-heater 1 is too high ((much) higher than saturation temperature), e.g. because there is no liquid flow.

PR1_alarm flag:

The PR1_alarm bit is set Not_Ok if: Pt04> 35ºC

PR1_alarm action

Disable pre-heater 1.

PR2_alarm: Health-guard: Pre-heater 2 temperature too high

Hazard

The temperature at the pre-heater 2 is too high ((much) higher than saturation temperature), e.g. because there is no liquid flow.

PR2_alarm flag:

The PR2_alarm bit is set Not_Ok if: Pt05> 35ºC.

PR2_alarm action

Disable pre-heater 2.

LLW_alarm: Health-guard: Condenser lines WAKE health heaters temperature too high

Hazard:

The temperature of the condenser lines health heaters WAKE becomes too high.

LLW_alarm flag

The LLW_alarm bit is set Not_OK if Pt09 > +35 ºC

LLW_alarm action

Disable the condenser lines health heaters WAKE.

LLR_alarm: Health-guard: Condenser lines RAM health heaters temperature too high

Hazard

The temperature of the condenser lines health heaters RAM becomes too high.

LLR_alarm flag

The LLR_alarm bit is set Not_OK if Pt06> +35 ºC

LLR_alarm action

Disable the condenser lines health heaters RAM.

Note:

It is noted that the condenser lines health heaters are controlled by thermostats, not by a on/off control algorithm in the TTCE.

LPS_alarm: Healtguard: Low pump speed:

Hazard

The TECs dump heat withdrawn from the accumulator in the liquid lines, which might lead to local overheating or boiling if there is no or little flow. This has occurred during breadboard tests and should be prevented by health-guards. Also pre-heaters, start-up heaters and cold orbit heaters shall be disabled if there is no or little flow. If pre-heaters, start-up heaters or cold orbit heaters on/off control loops are in CLOSED_LOOP while there is low or no pump flow, the on/off control loops can not keep the temperatures locally at the setpoint as the used temperature sensors are not located near the heaters and the on/off control loops hence can only function properly when there is sufficient flow.

LPS_alarm flag

The LPS_alarm bit is set Not_OK if pump_speed < 2400 rpm.

LPS_alarm action

Disable operation of TECs, start-up heaters, pre-heaters and cold orbit heaters if the pump speed is below 2400 rpm.

GAC_alarm: Health-guard: Accu control ground test heaters temperatures too high

In addition to the above health-guards, there is an additional safeguard which is only useful during the use of the ground testing heaters.

Hazard

For ground testing of the accumulator control the accumulator is heated by ground test heaters (GAC) mounted on the accumulator body and not by the accumulator control heaters (FAC) mounted on the heat pipe. The hazard is that the temperature at the location of the accumulator control ground test heaters may become too high.

Purpose of this health-guard

GAC_alarm flag

The GAC_alarm bit is set to Not_OK if the accumulator temperature Pt03 > 65 ºC

GAC_alarm action

Disable the ground accumulator control test heaters.

3.2.3.3 Enabling/disabling of the health-guards alarm actions

The health-guards alarm actions can be enabled/disabled by sending Write data Type 0x0A, carrying the bit settings required for this purpose, to the active TTCE.

Their default status at TTCE power-on is: ENABLED

3.2.3.4 Health-guards alarm bits

The TTCE health-guards alarm bits can be retrieved by sending Read Data Type request 0x0A to the TTCE.

3.3 High level TTCS loop commanding and monitoring

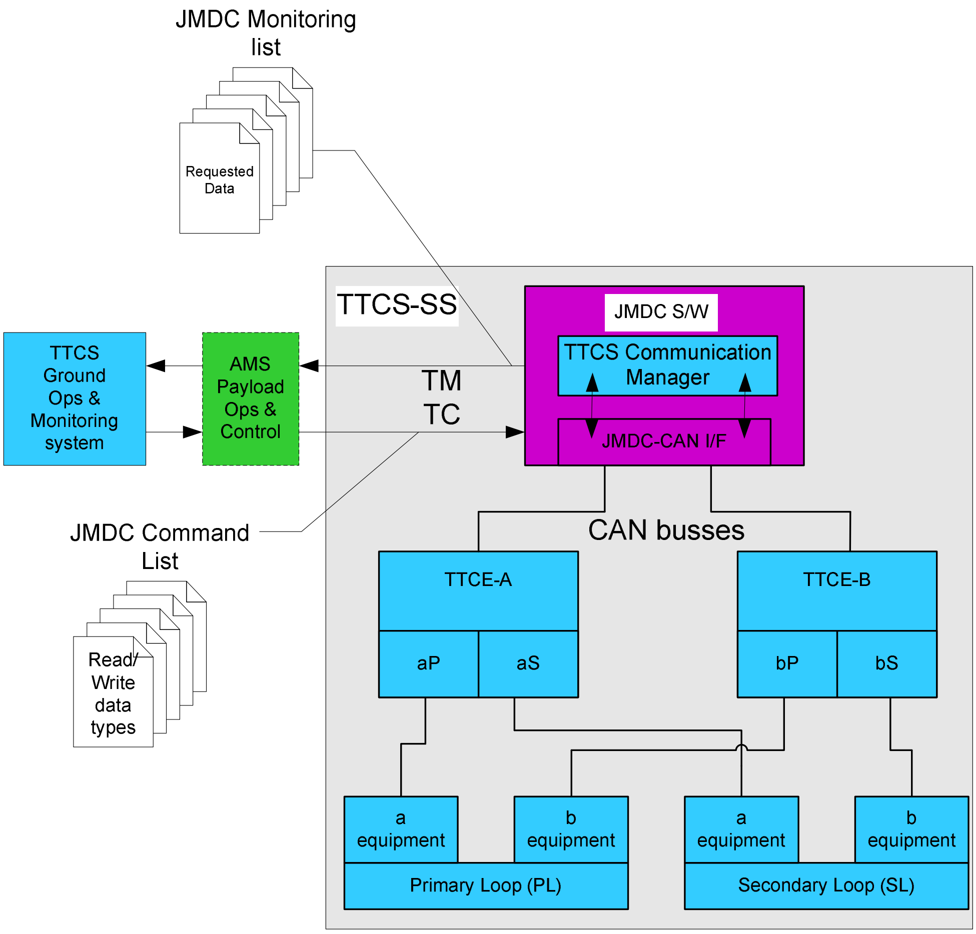
3.3.1 Introduction

At high level, the TTCS is commanded via sending Write Data Type requests to the active TTCE and the TTCS is monitored via telemetry acquired by sending (cyclical) Read Data Type requests to the TTCE.

The TTCS is monitored via telemetry acquired by sending Read Data Type requests to the TTCE.

A continuous telemetry data stream can be obtained by loading Data Polling Tables in the JMDC, which in its turn acquires the data from the TTCE via cyclical sending the appropriate Read Data Types from the Data Polling Table to the TTCE.

Likewise a single Read Data Type request can be sent once to the TTCE by the ground system to get one set of return data.



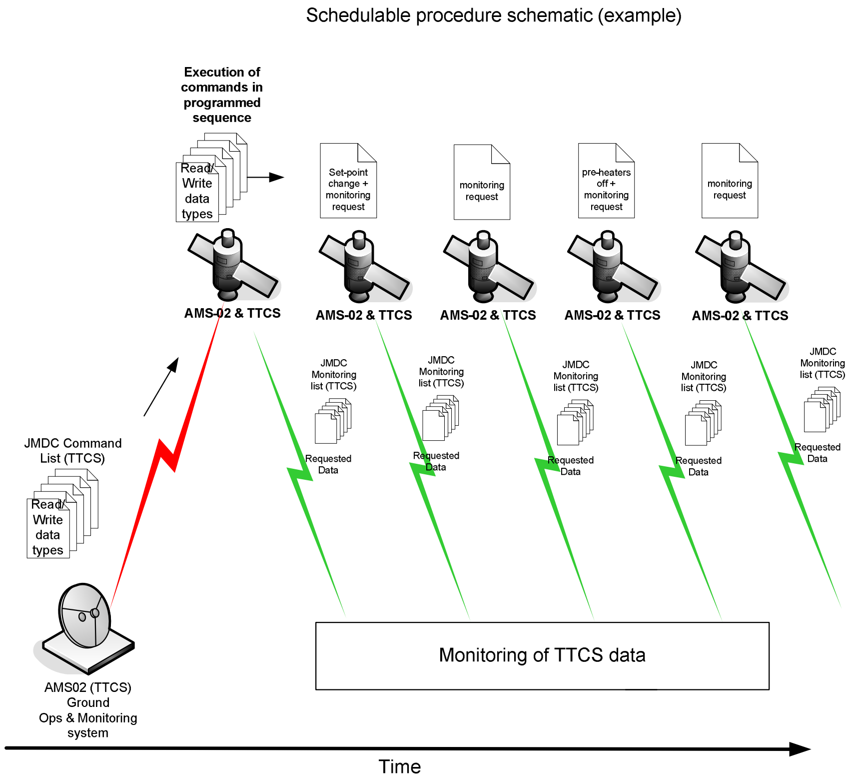
Figuur 3-1: High level commanding and monitoring schematic

The operation of the TTCs must adhere to strict procedures, in order to prevent operations errors.

At high level the TTCS is operated by sending Write Data Type requests to the TTCE.

The Write data Types to be sent to the TTCS are organized in operational procedures. For the TTCS two types of operational procedures are to be distinguished:

- schedulable procedures. This type of procedure contains single Write Data Types or sets of Write Data Types for immediate or time tagged execution. Time tagged execution means that a Write Data Type or set of Write Data Types is to be executed at the time point specified by the time tag. Immediate execution means that the commands are to be executed as soon as possible. The Write Data Types are sent from ground to the JMDC. The JMDC takes care of sending the Write Data Types at the right time to the TTCE. This type of schedulable operations comprise most normal routine operations when the TTCS has been started-up and is actively cooling the Tracker, such as: accumulator setpoint changes required for hot, nominal and cold orbits, disabling pre heater control in hot orbits and consequent enabling in nominal and cold orbits, etc. That is, all normal routine operations that can be scheduled in time.



Figuur 3-2: Schedulable procedures

- non-schedulable procedures. Non-schedulable procedures do not fit in the time tagged execution paradigm of the JMDC command list. These procedures consist of sequences of Write Data Types separated by decision criteria. On basis of the decision criteria it is to be decided whether or not it is allowed to send the next Write Data Type or set of simultaneous Write Data Types to the TTCE. That is, after each command or set of simultaneous commands to the TTCE, it is the task of the TTCS operator (and possibly the Tracker operator as well) to monitor the TTCS status (e.g. temperatures) and to wait and see if the criteria for sending the next command or set of simultaneous commands are met. This type of procedure is to be executed step by step while monitoring telemetry. This requires a continuous telemetry stream from the TTCS to the TTCS Ground Operations and Monitoring System. In fact this type of operation can only be done from ground, having real-time contact with the TTCS. Until now non-schedulable procedures which have been identified comprise only operations related to TTCS start-up. The non-schedulable procedures may pose a problem for the TTCS operations. Therefore it has been decided to define these procedures in advance and to pre-program them as far as possible in JMDC software, such that they can be executed semi-autonomously by the JMDC, where the JMDC plays the role of the TTCS operations expert taking decisions on basis of monitored telemetry. In this way the required downlink bandwidth is reduced. A number of procedures to be implemented in the JMDC, currently only related to TTCS start-up, have been defined in Chapter 8.

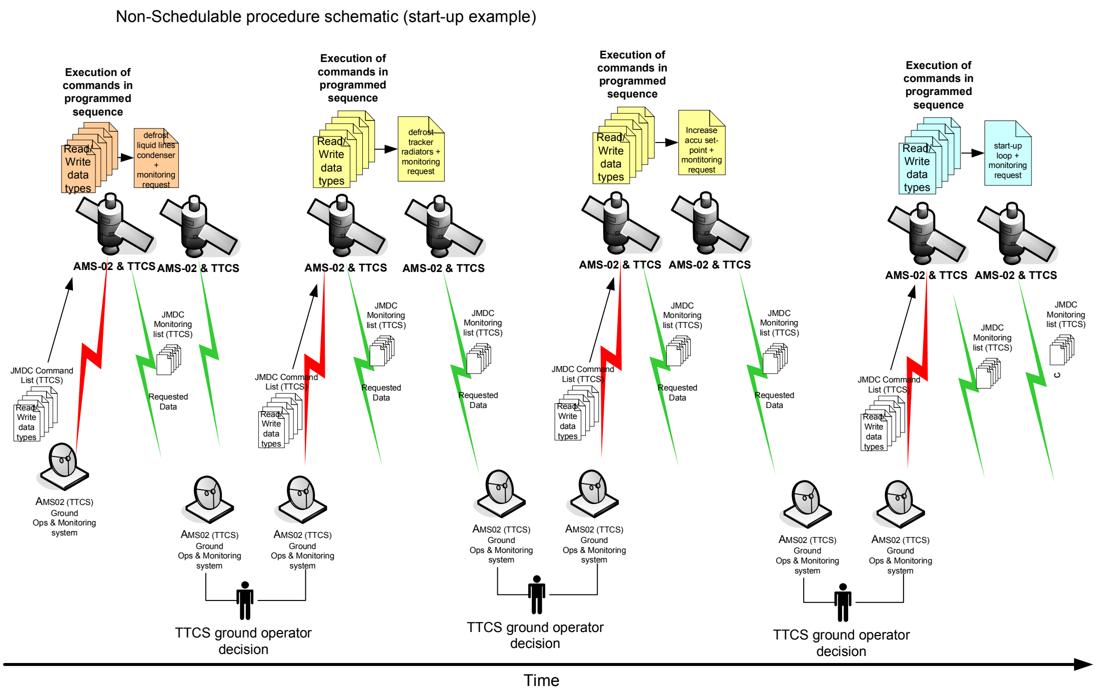


Figure 3-3: Non-schedulable procedures

Two systems for TTCS commanding and monitoring are currently foreseen:

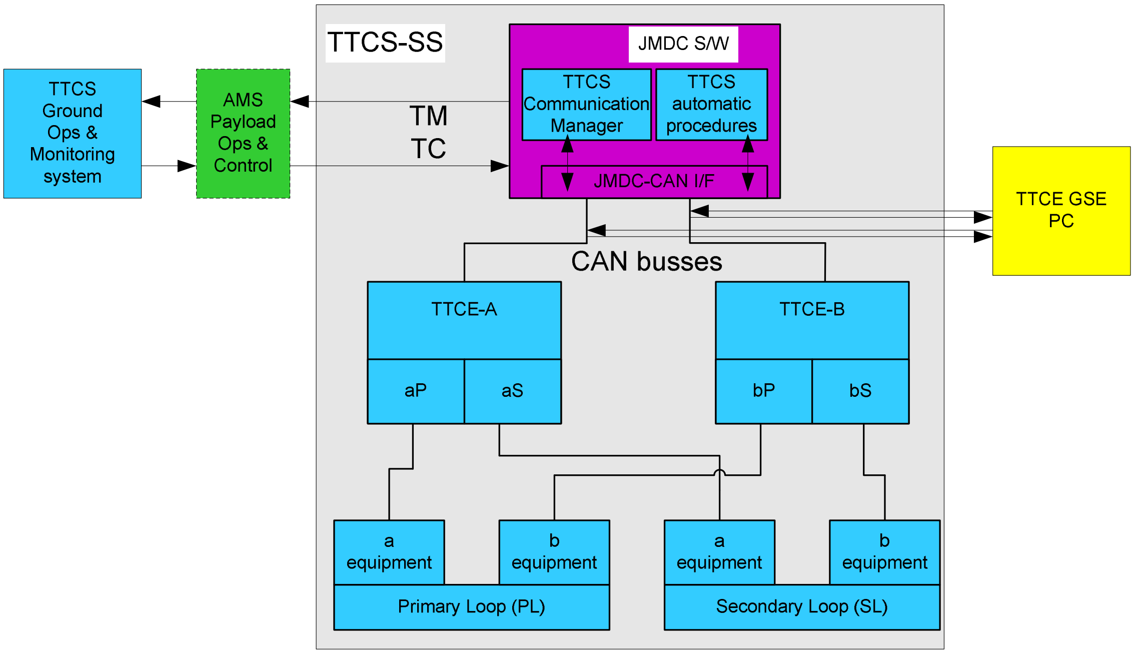


Figure 3-4:Flight and GSE commanding set-up

1. The TTCE Ground Support Equipment. The TTCE GSE is PC-based. The TTCE GSE interfaces directly with the TCCE via a connection on the CAN bus. Write Data Type requests are sent by the operator directly to the TTCE and telemetry is acquired via (cyclical) sending of Read Data Types. This system is used at CERN ESTEC and KSC. The TTCE GSE may also interface to the TTCS via the JMDC, e.g. at ESTEC and KSC. All operations on the TTCS are performed by the TTCS operator while directly monitoring telemetry from the TTCE.
2. The TTCS Ground Operations and Monitoring System. This system will be used during flight. The TTCS Ground Operations and Monitoring System interfaces with the AMS02 Payload Operations and Control System which further takes care of the data interface with the JMDC. For TTCS in-flight operations the difference between schedulable and non-schedulable operations, as described above, does play a role.
   2.1. Schedulable operations/procedures are performed from ground via putting a single command or set of commands in a "command list" loaded in the JMDC for immediate or time tagged execution. This type of schedulable operations comprise most normal operations when the TTCS has been started-up and is actively cooling the Tracker.

2.2. Non-schedulable procedures (currently only TTCS start-up related) are to be pre-programmed in the JMDC. Those procedures can be activated by a single telecommand from ground for further semi-automatic execution by the JMDC, where the JMDC plays the role of the TTCS operations expert taking decisions on basis of monitored telemetry.

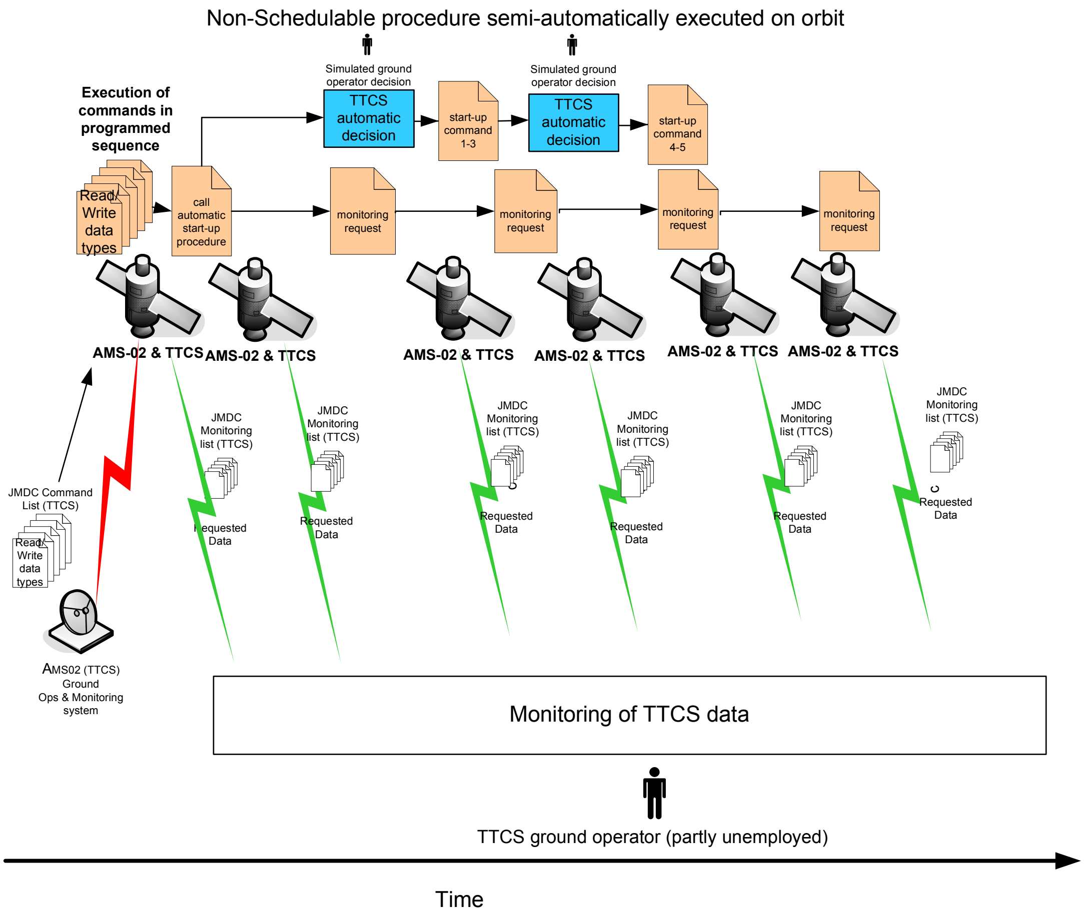


Figure 3-5: Semi-automatic programme

It is noted that the TTCS ground operator still has the option not to activate a loaded/programmed procedure and to execute the procedure completely from ground, while interactively monitoring the telemetry.

Note:

The TTCE GSE currently is existent and is used at CERN and will be used at ESTEC and KSC. The TTCS Ground Operations and Monitoring System is currently still to be designed.

An overview of all TTCS related Read and Write Data Types is given in Table 3-2. This information is taken over from Ref. 20.

Table 3-2 Overview of TTCE Read and Write Data Types

Data type nr	Read/Write request	Description
x01	Read	Ping
x05	Write	Start Erase Flash Sector
x05	Read	Erase Status (Not implemented)
x06	Read	Memory
x06	Write	Memory
x15	Write	Start DS scan
x15	Read	DS Scan Status
x16	Read	DS Control register
x16	Write	DS Control Register
x17	Read	DS ID table
x17	Write	DS ID table
x18	Read	DS Temperatures
x19	Read	Pt1000 temperatures
x19	Write	Pt1000 redundancy control
x1A	Read	Pressure sensors
x07	Write	28 V Control
x07	Read	28 V control
x08	Write	Pump Control
x08	Read	Pump Control
x09	Write	PWM Control
x09	Read	PWM Control
x03	Read	Execute Configuration file
x1B	Write	Delay 10 msec
x0A	Write	Loop Control
x0A	Read	Loop Control

3.3.2 High level TTCS Loop commanding

The Write Data Types directly involved in the commanding of the TTCS are, see Table 3-2:

- x07: 28V Control: Switching on/off 28V supply power for heaters, TECs, pumps
- x08: Pump Control: Setting of the pump speed setpoint
- x09: PWM Control: Manual control setting of PWM duty cycle
- x0A: Loop Control: Setting/Changing of Loop Control parameters:
    - Setting of control loops parameter values
    - Enabling/disabling of control loops (on/off and PI loops)
    - Enabling disabling of health-guard actions

A high level description of the above Write Data Types is given in the following sections. The detailed low level definition at bit and byte level of all relevant Data Types is beyond the scope of this document, but is known by Mr Vladimir Koutsenko and Mr Alexei Lebedev.
This information is not available to NLR. It is unknown if this information is documented.

3.3.2.1 Write Data Type x07: Commanding of 28V power switches

Write Data type x07 is defined in Table 3-3 below, which has been taken over from Ref. 20.

Table 3-3 Write Data Type x07: Commanding of 28V supply power for heaters, TECs, pumps, TTCEs

Data Type	Read/Write request	description
x07	**Write**	**28 V control**
		Request data: 8 bytes Reply: done There are 16 different heaters each powered by 28V through 2switches (E_, M_,) connected in series. There is one control bit for each switch (E_ bit M_bit). Control bit == 0-> switch is OFF. Control bit == 1 -> switch is ON. The control bits are implemented by two flip-flops: one for the E_ switch and one for the M_ switch. In the command with data type 0x07 (+0x40 because write command) there are three bits: set E, set M, and Write Enable. The command execution is described by the logic table: (info V. Koutsenko)

Write Command bits				resulting switch control bits value NC = no change	
set E	set M	Write Enable	->	E_	M_
0	0	0	->	NC	NC
0	1	0	->	NC	NC
1	0	0	->	NC	NC
0	0	1	->	0	0
0	1	1	->	0	1
1	0	1	->	1	0
1	1	1	->	1	1

Further definition of write data type x07

		switch name	Set value byte & bit	Write Enable bit byte & bit
		E_LLW_P	0 0	2 0
		E_LLR_P	0 1	2 1
		E_PR1_P	0 2	2 2
		E_PR2_P	0 3	2 3
		E_COR_P	0 4	2 4
		E_SUP_P	0 5	2 5
		E_GAE_P	0 6	2 6
		E_FAE_P	0 7	2 7
		M_LLW_P	1 0	2 0
		M_LLR_P	1 1	2 1
		M_PR1_P	1 2	2 2
		M_PR2_P	1 3	2 3
		M_COR_P	1 4	2 4
		M_SUP_P	1 5	2 5
		M_GAE_P	1 6	2 6
		M_FAE_P	1 7	2 7
		E_LLW_S	3 0	5 0
		E_LLR_S	3 1	5 1
		E_PR1_S	3 2	5 2
		E_PR2_S	3 3	5 3
		E_COR_S	3 4	5 4
		E_SUP_S	3 5	5 5
		E_GAE_S	3 6	5 6
		E_FAE_S	3 7	5 7
		M_LLW_S	4 0	5 0
		M_LLR_S	4 1	5 1
		M_PR1_S	4 2	5 2
		M_PR2_S	4 3	5 3
		M_COR_S	4 4	5 4
		M_SUP_S	4 5	5 5
		M_GAE_S	4 6	5 6
		M_FAE_S	4 7	5 7
		There are 6 regulated voltage (PWM) loads powered by 28 V trough one switch each and 2 pump 28 V pwr switches		
		E_GAC_P	6 0	7 0
		E_FAC_P	6 1	7 1
		E_TEC_P	6 2	7 2
		E_GAC_S	6 3	7 3
		E_FAC_S	6 4	7 4

		E_TEC_S	6 5	7 5
		P_P	6 6	7 6
		P_S	6 7	7 7

The Write Data Type x07 is used to provide power for the heaters, TECs and pump to be used further in closed loop control. The Write Data type x07 can also be used to "manually" switch heaters ON/OFF (LLW, LLR, PR1, PR2, COR, SUP).

Note.
The GAE and FAE heaters have been skipped, although their switches are present.

3.3.2.2 Write Data Type x08: Setting of SCV code value for pump speed setpoint

Write data Type x08 is defined in Table 3-4, which has been taken over from Ref. 20.

Table 3-4 Write Data Type x08: Setting of analogue voltage parameter value for pump speed setpoint

data type nr	Read/Write request	description
x08	Write	Pump control
		Request data; 2 byte Reply: DONE Byte 0: SCV_P Speed control voltage forPump in prime loop Byte 1 SCV_S Speed control voltage for Pump in Secondary Loop Control voltage: mV=4096*SCV Code/256) [mV]

Below a calibration graph of the required analogue Speed Control Voltage [mV] as function of the desired pump speed [rpm] is given.

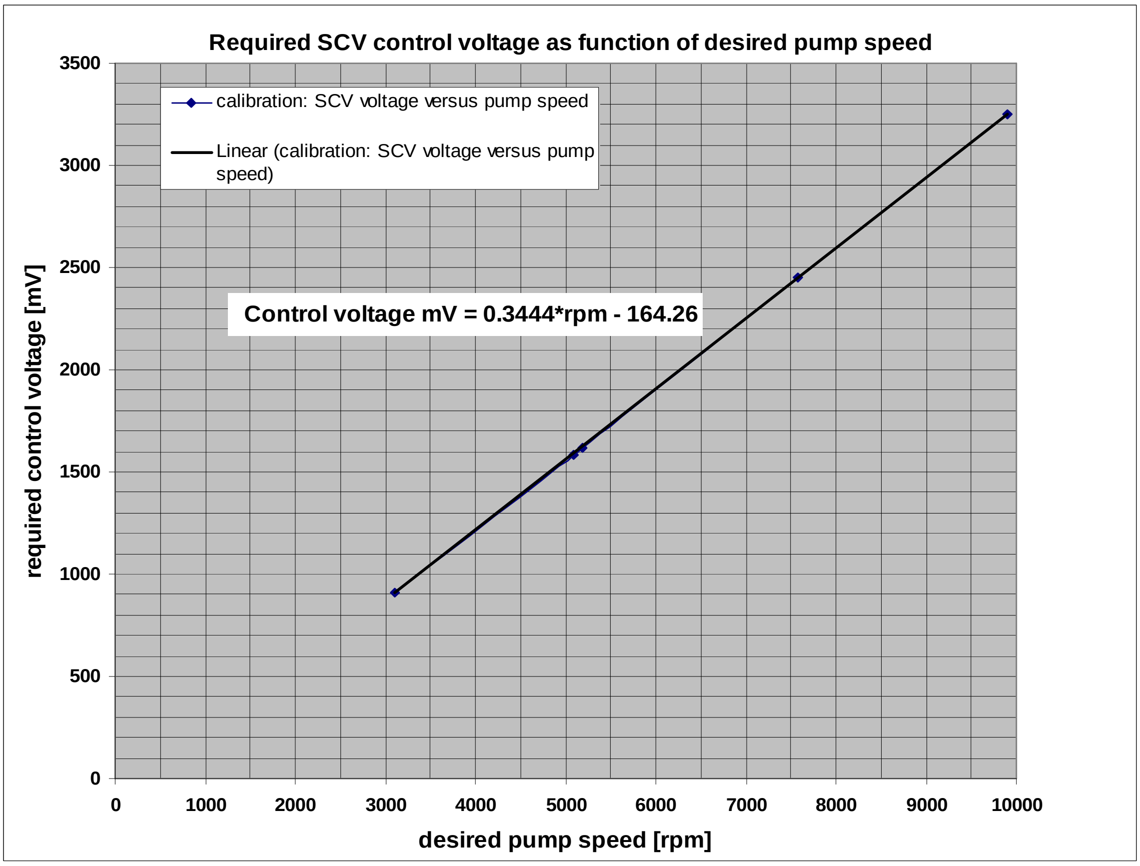


Figure 3-2 Required speed control voltage [mV] as function of the desired pump speed.

The linear interpolation formula of the required Speed Control Voltage as function of desired pump speed is, see Figure 3-2:

Speed Control Voltage: mV = 0.3444*rpm – 164.26;

For the Speed Control Voltage setting, see Write Data Type x08

The Speed Control Voltage has a range from 0 to 4096 mV.

The Speed Control Voltage is set via the SCV-code word which is unsigned bit: 0 to 255 :So:

Speed Control Voltage: mV = 4096*SCV Code/255)

The required SCV code as function of the pump speed now can be calculated from:

SCV code = rpm* (0.344*255/4096) -164.26*255/4096

The required SCV code value (integer only) can be read from the chart, Figure 3-3

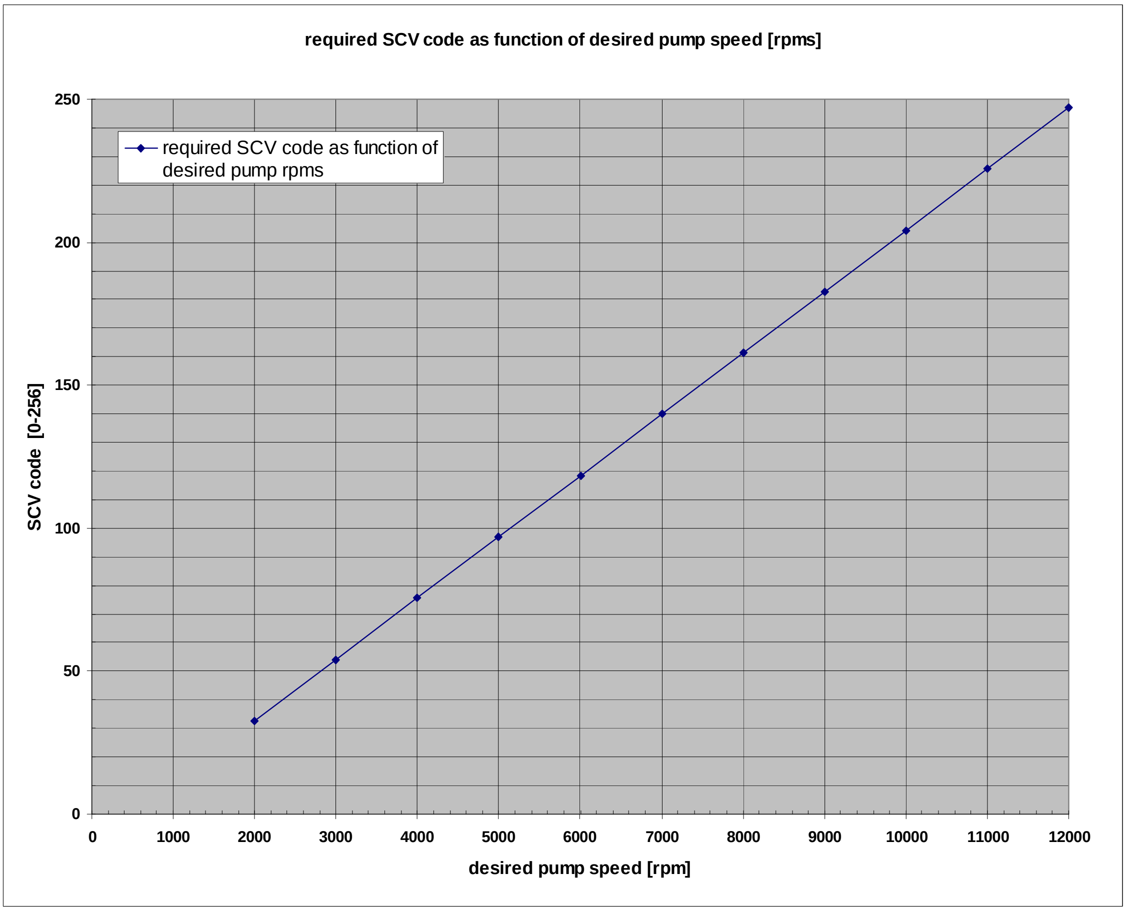


Figure 3-3 Speed Control code (integer value) as function of required pump speed [rpm]

3.3.2.3 Write Data Type x09: Manual setting of PWM duty cycle

Normally, the duty cycles of the PWMs are set via their associated closed loop control algorithms, if those are enabled.

However, the duty cycles can also be set manually via Write Data Type x09.

Write data Type x09 is defined in Table 3-5, which has been taken over from Ref. 20

Table 3-5 Write Data Type x09: Manual control setting of PWM duty cycle

data type nr	Read/Write request	description
x09	Write	PWM control
		Request data: from 2 to 12 byte Reply: DONE Two bytes per PWM controller Byte 0; Address (0 5 valid)

		Byte 1:DCV Duty Cycle value PWM controller output is 0V (OFF) if DCV == 0 Duty Cycle 99.6% if DCV == 255 address DCV_GAC_P 0 DCV_FAC_P 1 DCV_TEC_P 2 DCV_GAC_S 3 DCV_FAC_S 4 DCV_TEC_S 5

3.3.2.4 Write Data Type x0A: Setting of Loop control parameter values

Write data Type x0A is defined in Table 3-6, which has been taken over from Ref. 20.

The control loop parameters have default values at TTCE power-on. Loop control parameter values can be changed via sending Write Data type x0A (see Table 3-6).

Table 3-6 Write data Type x0A: Setting of Loop Control parameters

data type nr	Read/Write request	description
x0A	Write	Loop control
		Request data: from 2 to 128 byte Reply: DONE Two bytes per parameter Byte 0: Address (0 63 valid) Byte1 parameter value

In Table 3-7 below an overview of TTCS loop control parameters and variables and their default values at TTCE power-up is given. An identical table of variables and parameters can be compiled for the Secondary Loop. This information was taken over from Ref. 20

Table 3-7 TTCS Primary Loop parameters and their default values at TTCE power-on

address	Name	Bit nrs	description	Default value at power-on
x00	Control	5-4	range	0
		3	heat RO	
		2	FG	1

addr ess	Name	Bit nrs	description	Default value at power-on
		1	test	0
		0	pi_enable	0
x01	Set_point (accu)	5-0	(-32 ºC + 31 ºC)	0 ºC
x02	k1	0-7	unsigned, 8 bit LSbit = 1 (0 - +255)	0x10 (= 16)
x03	k2.	0-7	unsigned 8 bit LSbit = 1/16 (0-+15.9375)	0x10 (= 1.0)
x04	k3	0-7	unsigned 8 bit LSbit = 1/32 (0-+7.96875)	0x10 (= 0.5)
x05	iband	0-7	unsigned 8bit LSbit = 1/16 (0- +3.9375)	0x10 = 1ºC
x06	Feed_forw	0-7	MSB signed 16 bits -32768 - + 32767	0
x07		0-7	LSB	0
x08	Test_T	0-7	4MSbits = 0 bits3-0 contain bits 11-8 of Test_T	0
x09		0-7	bits7-0 of Test_T,	0
x0A	ph_term	0-7	RO MSB signed 16 bit	depends on Pt01_P
x0B		0-7	RO, LSB	depends on Pt01_P
x0C	ih_term	0-7	RO, MSB signed 16 bit	0
x0D		0-7	RO, LSB	0
x0E	pi_dcv		RO unsigned char	
x0F	cav_margin	0-4	LSbit = ½ ºC (0-15.5 ºC)	0x0A (= 5ºC)
x10	LLW_Loop	0-5	LLW setpoint (-32 - +31)	0x20 (= -31 ºC)
		6	LLW_enable	LLW_enable = 0
		7	LLW_out	LLW_out = 0
x11	LLR_Loop	0-5	LLR setpoint (-32 - +31)	0x20 (= -31 ºC)
		6	LLR_enable	LLR_enable = 0
		7	LLR_out	LLR_out = 0
x12	PR1_Loop	0-5	PR1 setpoint	0x20 (= -4 ºC)
		6	PR1_enable	PR1_enable = 0
		7	PR1_out	PR1_out = 0
x13	PR2_loop	0-5	PR2 setpoint	0x20 (= -4 ºC)
		6	PR2_enable	PR2_enable = 0
		7	PR2_out	PR2_out = 0
x14	COR_Loop	0-5	COR setpoint	0x20 (= -31 ºC)
		6	COR_enable	COR_enable = 0
		7	COR_out	COR_out = 0
x15	SUP_Loop	0-5	SUP setpoint	0x20 (= -31 ºC)
		6	SUP_enable	SUP_enable = 0
		7	SUP_out	SUP_out = 0
x16	alarm_ena	0	CAV	0xFF (all alarms enabled)
		1	TRK	
		2	PR1	
		3	PR2	
		4	LLW	
		5	LLR	
		6	LPS	
		7	GAC	
x17	alarm_now	0	CAV	depend onPt01_P - Pt09_P readings
		1	TRK	
		2	PR1	
		3	PR2	
		4	LLW	
		5	LLR	
		6	LPS	
		7	GAC	
x18	alarm_was	0	CAV	depend on previous Pt01_P - Pt09_P readings
		1	TRK	
		2	PR1	

address	Name	Bit nrs	description	Default value at power-on
		3	PR2	
		4	LLW	
		5	LLR	
		6	LPS	
		7	GAC	
x19			cycle_cnt	# of cycles after power-on (modulo 256)
x1A			not defined	0
x1B			not defined	0
x1C			not defined	0
x1D			not defined	0
x1E			not defined	0
x1F			not defined	0
			x20 – x3F set of the same parameters for Secondary Loop	

It is noted that TTCE-A and TTCE-B each implement these tables, such that TTCE-A can be used to operate the **A equipment** of the Primary Loop or the Secondary Loop or the TTCE-B can be used to operate the **B equipment** of the Primary Loop or Secondary Loop

3.3.2.5 In Flight-Loop Control parameters K1, K2, K3, range and iband values

The above listed power-on default values for K1, K2, K3, range and iband should not be used operationally.

The following set of parameters which have proven to be optimal in earthly conditions, is to be used.

Table 3-8 Loop Control parameter values k1, k2, k3, range, iband to be used in-flight.

parameter name	parameter nr	size, LSbit value, scaled range	scaled value to be used	remark
range	x00 bits 5-4	unsigned 2 bits, (0 – 3), LSbit = 1 scaled range (0 – 3)	1	p range = ±0.9375 ºC
k1	x02	unsigned 8 bit, (0 - 255), LSbit = 1 scaled range (0 - 255)	255	
k2	x03	unsigned 8 bit, (0 – 255), LSbit = 1/16 scaled range (0 - 15.9375)	15.9375	
k3	x04	unsigned 8 bit, (0 – 255), LSbit = 1/16	7.96875	

		scaled range (0 – 7.96875)		
Iband	x05	unsigned 8 bit, (0 -255), LSbit = 1/16ºC scaled range (0 – 3.9375)	1 ºC	slightly larger than p range

Below, two other sets of parameters are given. Those sets cause slower control behaviour of the TTCS. So they should not be used unless a TTCS operations expert has reason to do so.

parameter name	parameter nr	size, LSbit value, scaled range	scaled value to be used	
range	x00 bits 5-4	2 bits , (0 - 3), LSbit = 1, scaled range (0 – 3)	2	p range = ±1.9375 ºC
k1	x02	unsigned 8 bit, (0 – 255), LSbit = 1 scaled range (0 - 255)	255	
k2	x03	unsigned 8 bit, (0 – 255), LSbit = 1/16 scaled range (0 - 15.9375)	10 to 5	
k3	x04	unsigned 8 bit, (0-255), LSbit = 1/16 scaled range (0 – 7.96875)	7.96875	
iband	x05	unsigned 8 bit (0-255), LSbit = 1/16ºC scaled range (0 – 3.9375 ºC)	2 ºC	

parameter name	parameter nr	size, LSbit value, scaled range	scaled value to be used	
range	x00 bits 5-4	2 bits , bits 5-4 of x00 scaled range (0 – 3)	0	p range = ±3.9375 ºC
k1	x02	unsigned 8 bit LSbit = 1 scaled range (0 - 255)	255	
k2	x03	unsigned 8 bit LSbit = 1/16 scaled range (0 - 15.9375)	5 to 1	
k3	x04	unsigned 8 bit LSbit = 1/16 scaled range (0 – 7.96875)	7.96875	
iband	x05	unsigned 8 bit LSbit = 1/16ºC scaled range (0 – 3.9375)	3.9375 ºC	equal to p range

It is noted that the iband must be chosen slightly larger, or equal to, the p range. The p range depends on the chosen range value, see above.

A larger iband causes a larger band where control error integration takes place and hence will cause larger overshoot, and possibly oscillatory behaviour if k2 is kept constant. Therefore k2 is chosen smaller if a larger range and iband are selected. If k2 = 0 is selected only proportional control is active, which will cause a hang-off w.r.t . the setpoint.

3.3.2.6 Important notes

The E_ control bit of a 28V power switch must be (set to) = 1 while the associated loop is under closed loop control.

The alarm action bits do not change the value of the E_ or M_ control bits of the 28V power switches, but suppress the E_ bit action, according to the logic Table 3-9.

Table 3-9 Heater status as function of an associated alarm bit

E_ bit	Alarm bit	Heater status
0	0	OFF
1	0	may be ON
0	1	OFF
1	1	OFF
The information in this table has been supplied by Mr. V. Koutsenko		

It is noted that an E_ bit action may be suppressed by more than one associated alarm bit, see section 3.2.3.

For each heater with loop control the results of the _out bit and _enable bit is described by the logic Table 3-10.

Table 3-10 Heater status as function of associated _out bit and _enable bit.

M_ bit	_out bit	_enable	Heater status
0	X	0	OFF
1	X	0	ON if E==1 Else OFF *)
X	0	1	OFF
X	1	1	ON if E==1 Else OFF *)
The information in this table has been supplied by Mr. V. Koutsenko			

X = does not care

*) note that if alarm bit == 1 while E_ bit == 1 heater is OFF.

3.3.3 High level TTCS monitoring

3.3.3.1 Introduction

The current baseline is to monitor TTCS operational statuses and temperatures on the ground, by the TTCS Ground Operations and Monitoring System.

A continuous-time monitoring data stream can be obtained by loading Data Polling Tables in the JMDC, which in its turn acquires the data from the TTCE via sending the appropriate Read Data Types.

An overview of the Read Data Types is given in Table 3-2 above.

3.3.3.2 Proposed routine in-flight TTCS monitoring Data Polling and down-link

The Read Data Types and their response data sizes which are most important for TTCS operation monitoring are given below in Table 3-11 below.

Table 3-11 Read Data Types and their response data sizes for TTCS monitoring

Data type nr	Request	Description	Read request reply bytes	
x19	Read	Pt1000 temperatures	44	
x1A	Read	Pressure sensors	8	
x07	Read	28 V control	5	
x08	Read	Pump Control	6	
x09	Read	PWM Control	6	
x0A	Read	Loop Control	64	
x18	Read	DS temperatures	96 (4buses, 46 sensors in total)	
total			229 bytes = 1832 bit	

It is proposed to have the JMDC execute this set every 10 seconds.

This leads to a mean TTCS monitoring downlink bit rate of 183.2 bits/second.

Note:

Note that the overall performance of the TTCS can be monitored from the distribution of the temperatures measured by the Dallas sensors mounted on the evaporators. Hence monitoring of the Dallas sensors is very important and very useful.

3.4 APS mean linear calibration curve averaged over all APSs

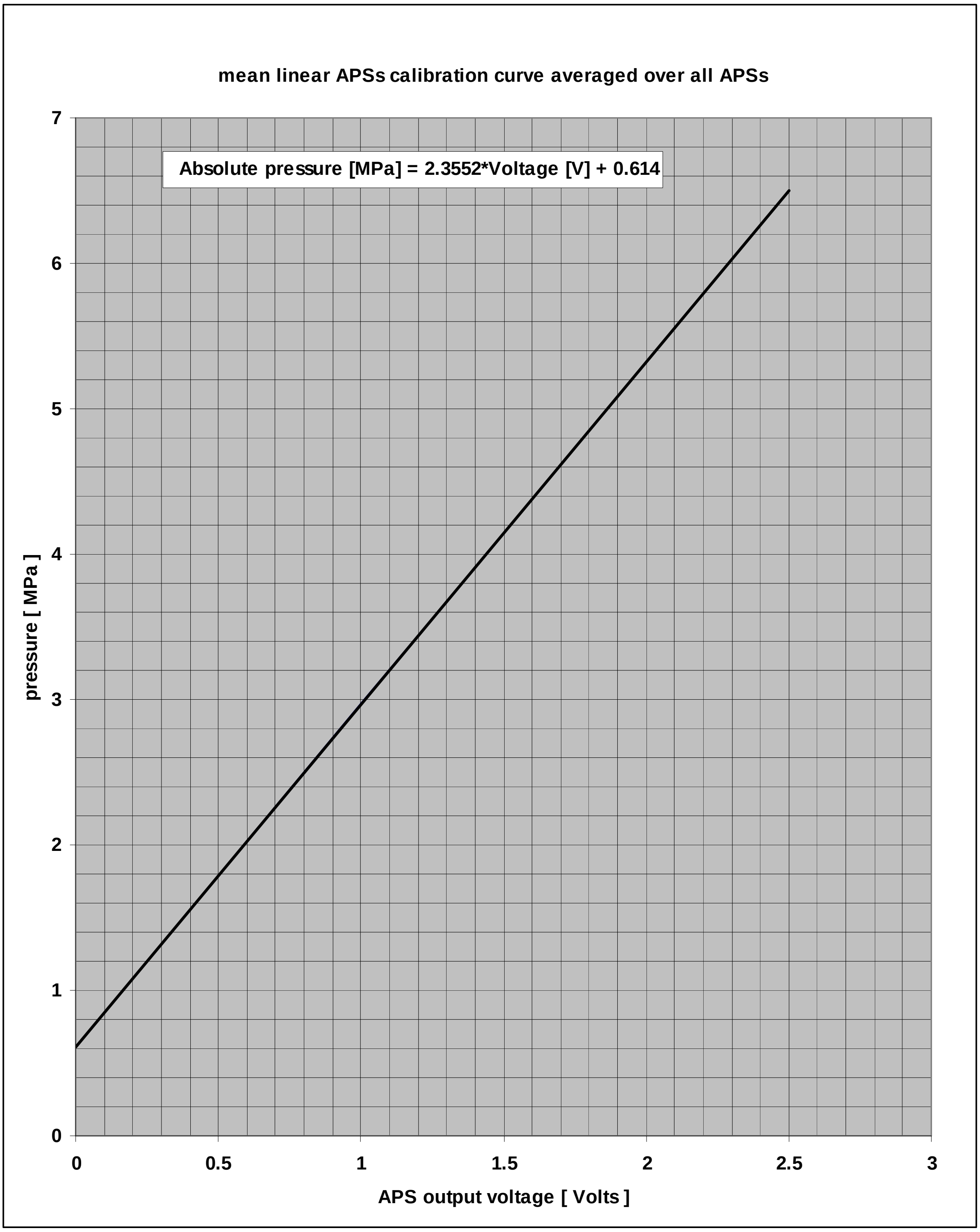


Figure 3-4 Mean linear APS calibration curve averaged over all APSs

3.5 Mean linear DPS calibration curve averaged over all DPSs

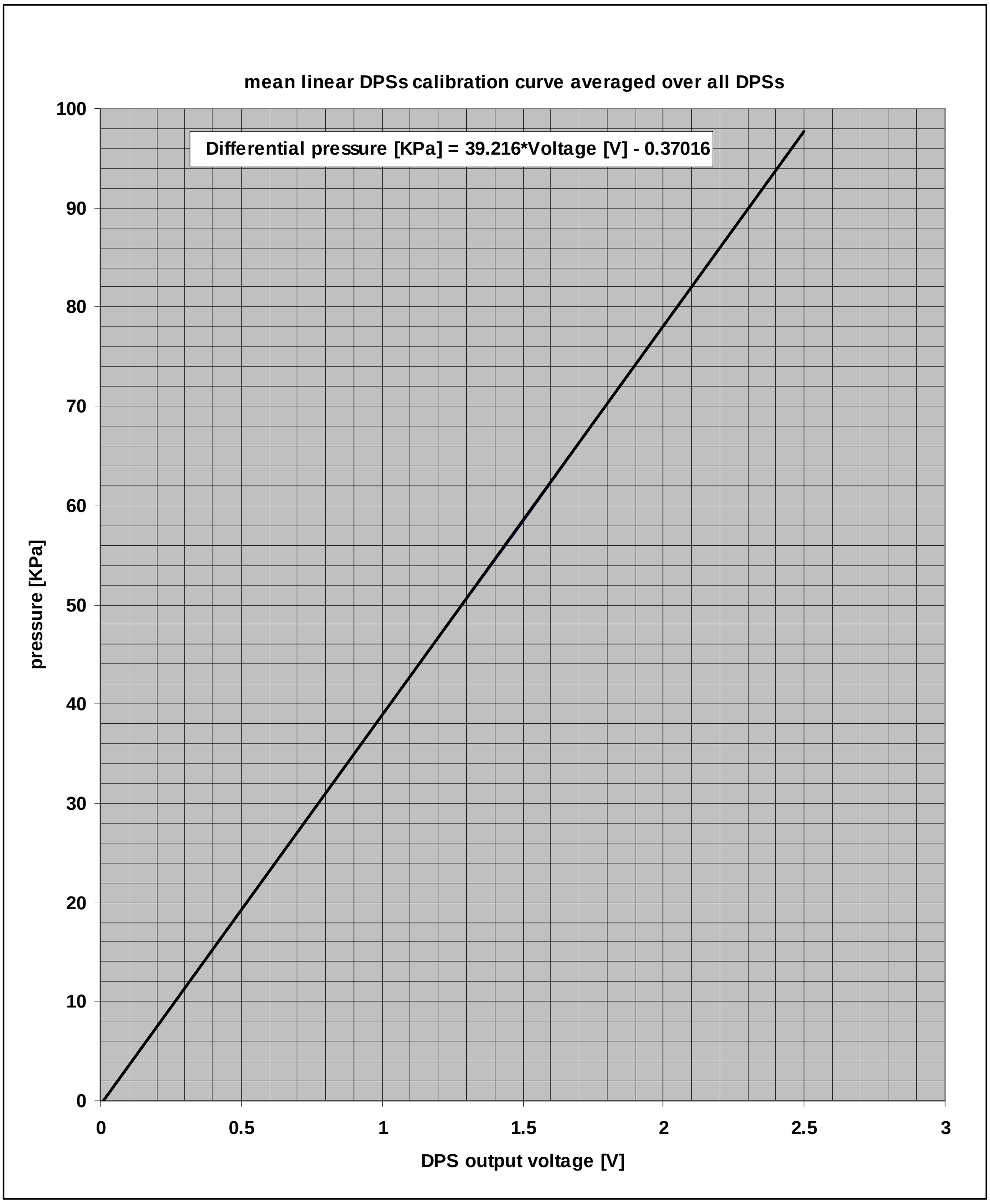


Figure 3-5 Mean linear DPSs calibration curve averaged over all DPSs

4 The TTCS Ground Support Equipment used at CERN/ESTEC/KSC

At CERN a control and monitoring system for the TTCS, called TTCS Ground Support Equipment, has been implemented. The Graphical User Interface has been split over two screens, given below, see Figure 4-1 and Figure 4-2.
This system will also be used at ESTEC and KSC.

Note:
It is noted that the control and monitoring system at CERN can service one operational TTCE.
If it must be possible to have TTCE-A and TTCE-B simultaneously operational, there must be two TTCS control and monitoring systems simultaneously active.

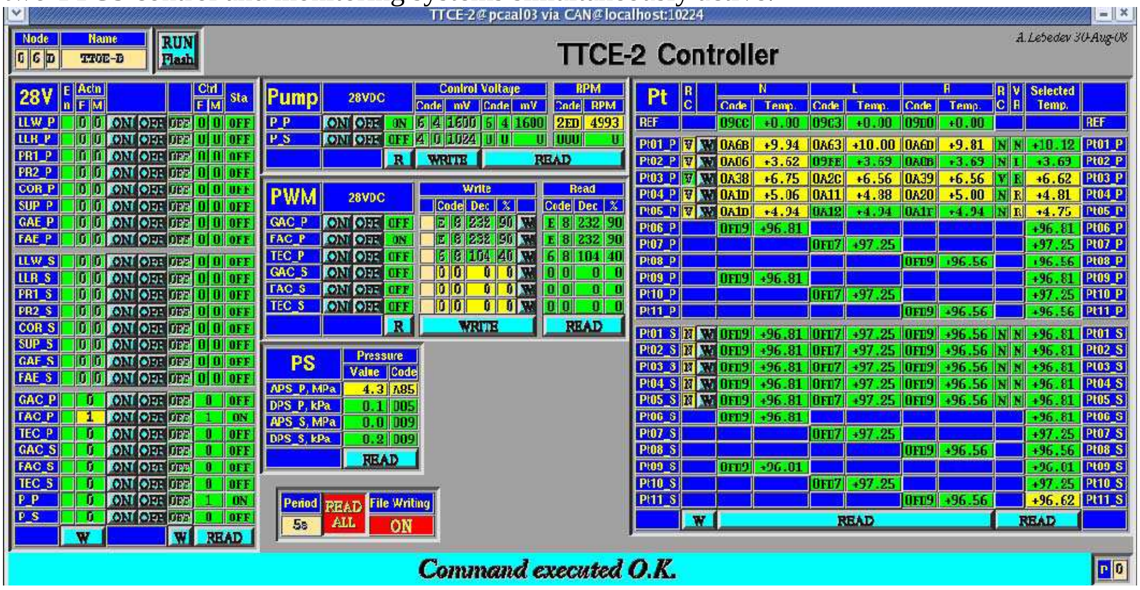


Figure 4-1 TTCS control and monitoring Graphical User Interface

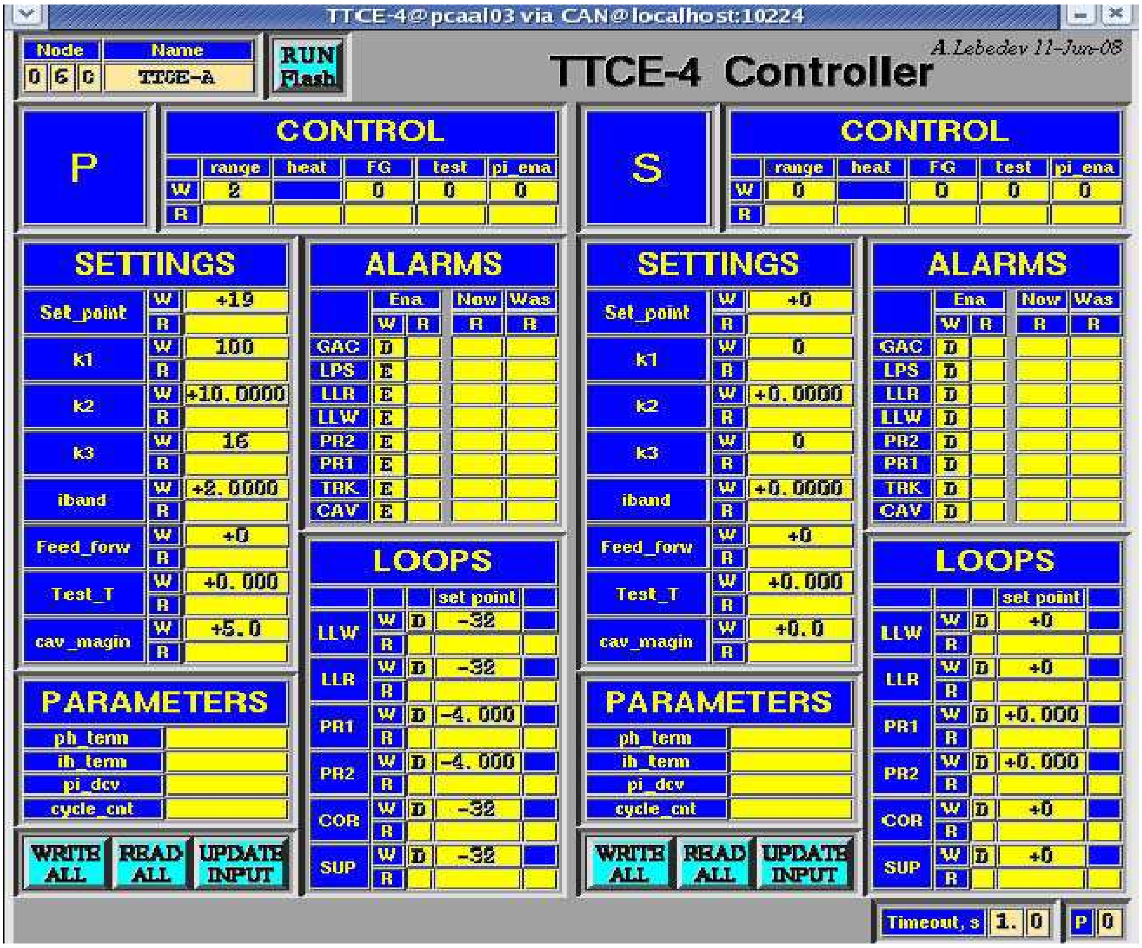


Figure 4-2 TTCS Loop control and monitoring Graphical User Interface.

5 The TTCS Ground Operations and Monitoring System

TBW

6 The JMDC command list

TBW

7 Proposed high level TTCS health-guards in JMDC

7.1 Introduction

Three health-guards could not be implemented in the TTCE, as they require actions at a higher level. Therefore it is required to implement these healthguards in the JMDC.

The health-guards proposed at JMDC level are:

- **Overall Tracker Electronics high and low temperature health-guard**
  Purpose: To provide an overall independent protection of the Tracker Electronics for too high and too low temperatures.
- **Radiator freezing health-guard**
  Purpose: To warn for freezing of the radiators, which may occur during periods when the PDS does not supply power to the radiators health heaters.
- **JMDC-TTCE communication outage health-guard (in TTCE-Manager)**
  Purpose: Protect the Tracker Electronics for possibly hazardous malfunctioning of the TTCS during a TTCE-JMDC communication outage.

7.2 Overall Tracker Electronics high and low temperature health-guard

7.2.1 Hazard

Too high or too low Tracker Electronics temperature during Tracker operation, e.g. caused by unnoticed TTCS malfunction or unexpected TTCS operational behaviour.

7.2.2 Purpose of this health-guard

To provide an overall protection for the Tracker Electronics for operation at too high or too low temperatures, outside the operational range of the Tracker Electronics.

The Tracker Electronics temperature is directly is monitored by means of a number of digital Dallas temperature sensors which are mounted on the evaporators.

The operating temperature range of the Tracker Electronics is from -10 ^{0}C to + 25 ^{0}C

The survival temperature range of the Tracker Electronics is from -20 ^{0}C to + 40 ^{0}C

It is allowed to switch-on the Tracker Electronics while it is in the lower range of its survival temperature range (-20 ^{0}C).

7.2.3 Health-guard action analysis

It is proposed to switch-off and prevent switching-on the Tracker Electronics if the monitored temperatures (e.g. readings of two or more healthy Dallas sensors) are not within the allowed range - 20 ^{0}C to +25 ^{0}C.

7.2.4 Monitored variables

Evaporator temperature determined from a TBD set of Dallas temperature sensors mounted on the evaporators. In the current design, the Dallas temperature sensors are read by the TTCE located micro-controller that communicates with the JMDC via the CAN bus, and the Dallas sensor readings are not available in the low-level control FPGAs. Therefore it is proposed to implement this overall Tracker temperature health-guard in the JMDC.

Note :

Note that the overall performance of the TTCS can be monitored from (the distribution of) these temperatures, measured by the Dallas sensors. Hence monitoring of the Dallas sensors is very useful.

7.3 Radiators freezing health-guard

7.3.1 Hazard

Although autonomous thermostat controlled survival heaters are applied to the radiators, they will prevent the radiators from freezing only if the PDS provides power.

Radiators may freeze if the PDS does not provide power to the radiator heaters and the Tracker is not on.

In the current design, the PDS does not continuously provide power to the radiators survival heaters, so monitoring of the radiator temperatures is required, in order to signal a possible onset of freezing.

Furthermore, the radiators may be frozen at the time point when the JMDC and TTCE are powered-on. In that case the condenser lines must be de-frosted first before the radiator heaters may be powered-on.

7.3.2 Purpose of this health-guard

Prevent freezing of the radiators.

Prevent de-frosting of the radiators before the condensers have been defrosted.

7.3.3 Monitored variables

The temperatures of the radiators are measured by Pt8 and Pt11, the condenser lines inlet temperatures are measured by Pt7 and Pt10.

7.3.4 Health-guard action analysis

Freezing of the radiators can only occur if the PDS does not power the health heaters while the Tracker is not on.

This health-guard in the JMDC is to signal the onset of radiator freezing from the monitored temperatures (e.g. <- 50ºC) and has to (let) power-on the PDS power to the radiators health heaters.

However, it is emphasized that if the monitored temperatures turn out to be too low (<- 55ºC) immediately after TTCE and JMDC are powered-on, the radiator health heaters should not be powered-on, as in that case the condenser lines must be defrosted first, see section 8.3.1 TTCS start-up procedure.

Hence the proposed health-guard action is two-fold:

- (let) prevent power-on by the PDS of the radiator health heaters if, immediately after power-on of the JMDC and TTCE, the monitored radiators temperatures indicate freezing, i.e. Pt8 < -55 ºC or Pt11 < -55 ºC at start-up. In this situation it is likely that the radiators and condensers are frozen, so the PDS should not power the radiator heaters, before the condenser.
- (let) the PDS power-on the radiator health heaters in case the radiator temperatures decrease from above -50 ºC to below -50 ºC. In situations where the radiator temperatures decrease from above -50 ºC to below -50 ºC it is certain that the radiators and condensers are not yet frozen, so the radiators can be safely powered by the PDS, to prevent freezing

7.4 JMDC-TTCE communication outage health-guard

7.4.1 Hazard

Incorrect functioning of the active cooling Loop, while no information on the functioning of the Tracker cooling is available, due to a TTCE-JMDC communication failure

7.4.2 Purpose of this safeguard

Protect the Tracker Electronics for possibly hazardous malfunctioning of the TTCS, after a TTCE-JMDC communication outage

7.4.3 Monitored variables

The duration of communication outage duration can be measured by software in the JMDC by counting (missed) TM cycles of TTCE-A and/or TTCE-B.

7.4.4 -TTCE-JMDC communication outage health-guard action analysis

If the communication between an active TTCE and JMDC fails, there is neither information in the JMDC available about the correct functioning of the TTCS, nor the **Overall Tracker Electronics high-low temperature safeguard** is able to function correctly.

Furthermore, there is no other independent (independent of the TCCS) measurement of the Tracker temperature available in the JMDC.

This is a potentially very dangerous situation for the Tracker Electronics that can not be tolerated for longer time periods, for as the TTCS would fail in such a time period the Tracker Electronics would burn-out.

Very short duration outages are tolerable, because, thanks to the thermal mass of the Tracker, the Tracker temperature will not react quickly on a TTCS failure.

The following health-guard actions can be considered:

1. switch-off the Tracker Electronics and
    1.1. let the unreachable TTCE continue operation
    1.2. stop the unreachable TTCE and TTCS via un-powering (via PDS)
2. leave the Tracker and unreachable TTCE "ON" and let the JMDC autonomously switch ”ON” (if not already "ON") the redundant TTCE and continue monitoring of the unreachable active cooling loop via the redundant TTCE. In principle, during a communication failure with the active TTCE it is possible to monitor the behaviour of the active cooling loop with the redundant TTCE if this one is "ON" **and healthy**. Also the Overall Tracker Electronics high-low temperature health-guard can continue to function correctly, now based on redundant data.
3. In case also the redundant TTCE appears to be unreachable, the Tracker shall be switched off after which also the TTCE must be powered-off via the PDS.

This second idea sheds a new light on the operational use of the redundant TTCE, e.g. one TTCE might be used for active control and the redundant TTCE might be switched-on in case of a communication failure or even might be "ON" continuously to provide redundant monitoring.

This second idea has not been worked-out yet, but it seems to be the preferred solution to survive short periods of communication outage of the active TTCE.

As during a communication outage the active cooling loop is not reachable, e.g. for accumulator setpoint changes, longer periods of persistent communication outage must be handled via reconfiguration to a redundant configuration. A reconfiguration involves powering-off the unreachable active TTCE and its equipment and powering-on the redundant loop equipment, control loops and pump.

It is required to switch-off the Tracker during such a reconfiguration and to perform a complete start-up procedure of the cooling loop.

Notes:

1. It is desirable to leave the unreachable TTCE "ON" during a communication failure, as there is no means for a controlled switch-off. However, continued operation of the loop with the Tracker Electronics "Off" will result in a gradual cool down of the liquid temperature and even may result in condenser freezing if the PDS is not powering the radiator survival heaters. To this end the radiators freezing health-guard was proposed, see previous section 7.3. However, this health-guard has to function on the data supplied by the redundant TTCE as the primary is unreachable.
2. It is highly desirable that there is a TTCE-independent overall Tracker Electronics temperature health-guard in the JMDC. It is noted that the proposed Overall Tracker temperature health-guard is not TTCE-independent.

8 TTCS operational rules and start-up related procedures

8.1 Introduction

In order to avoid mistakes in the remote operation of the TTCS, the TTCS is to be operated on basis of strict operational procedures.

For the TTCS two types of operational procedures are to be distinguished as has been described before:

- schedulable procedures. This type of procedure contains single Write Data Types or sets of Write Data Types for immediate or time tagged execution. The Write Data Types are sent from ground to the JMDC command list. The JMDC takes care of sending the Write Data Types at the right time to the TTCE. This type of schedulable operations comprise most normal routine operations that can be scheduled in time after the TTCS has been started-up and is actively cooling the Tracker.
- non-schedulable procedures. Non-schedulable procedures do not fit in the time tagged execution paradigm of the JMDC command list. These procedures consist of sequences of Write Data Types separated by decision criteria. On basis of the decision criteria it is to be decided whether or not it is allowed to send the next Write Data Type or set of simultaneous Write Data Types to the TTCE. That is, after each command or set of simultaneous commands to the TTCE, it is the task of the TTCS operator (and possibly the Tracker operator as well) to monitor the TTCS status (e.g. temperatures) and to wait and see if the criteria for sending the next command or set of simultaneous commands are met. This type of procedure is to be executed step by step while monitoring telemetry. This requires a continuous telemetry stream from the TTCS to the TTCS operator.

In fact non-schedulable operation can only be done from ground, having real-time contact with the TTCS. The amount of additional monitoring data required may pose a problem for the TTCS operations.

Therefore it has been decided to define these procedures in advance, as candidates for possible implementation in JMDC software.

In case of implementation in the JMDC software they can be executed semi-autonomously by the JMDC, where the JMDC plays the role of the TTCS operations expert, taking decisions on basis of monitored telemetry.

In this way no additional downlink bandwidth is required.

The currently identified non-schedulable procedures are related to TTCS start-up.

In this chapter the identified operational procedures for the start-up of the TTCS and the initial phases of the Tracker start-up are defined.

As an introduction some operational TTCS know how and operational rules to be taken into account are presented.
On basis of this information, a TTCS start-up procedure and some additional support procedures have been devised.
The procedures could be executed "manually" by Ground Control, but could also be implemented in software and executed "semi-autonomous" under control of the JMDC.
The term semi-autonomous is used here, as some information needed in the procedures may not be acquirable by the JMDC and still must be made available to the JMDC by ground command

As described in section 2.5 different operational configuration can be chosen.
The start-up procedure is written such that details of which TTCE (A or B) is operating and which Loop (Primary or Secondary) is started up is left out of the procedure.

It is emphasized, that the TTCS operator still has the option to execute the procedures associated with TTCS start-up "manually" at the ground, or to command the activation of the "autonomous start-up" in the JMDC.

8.2 TTCS operational rules for TTCS start-up and operation

1. Operational configuration selection

From the description of the redundancy concept in section 2.2 above it follows that there are different redundant configurations in which a cooling loop can be operated

1. TTCE-A powered on, controlling Primary Loop using "A" equipment
2. TTCE-A powered on, controlling Secondary Loop using "A" equipment
3. TTCE-B powered on, controlling Primary Loop using "B" equipment
4. TTCE-B powered on, controlling Secondary Loop using "B" equipment

First it has to be selected which TTCE (A or B) is powered on, next it is to be selected which Loop (Primary or Secondary is to be started up.
The TTCE power-on selection is as follows:
IF (TTCE-A ==HEALTHY) power-on TTCE-A
ELSE IF (TTCE-B == HEALTY) power-on TTCE-B
END
The Loop selection is done as follows.
IF (Primary Loop == HEALTHY) start-up Primary Loop
ELSE IF (Secondary Loop == HEALTHY) start-up Secondary Loop.
END

For the first-time in-flight start-up it is to be assumed that TTCE-A== HEALTHY and Primary Loop == HEALTHY.

Exceptional cases in which P and S loop equipment are operated simultaneously shall be dealt with on a case by case basis and operations should be performed under full ground monitoring and control.

2. Power-on of a TTCE

A TTCE may be powered-on at any time. Powering-on a TTCE can not endanger the TTCS system.

3. Status after TTCE power-on

- After TTCE power-on the relevant 28V power switches are still OFF

Default values for TTCS loop control parameters are given in Table 3-7, above.
In summary the status at TTCE power-on is:

- the 28 V power switches are OFF
- all on/off control loops are DISABLED
- pi control of the accumulator is DISABLED
- all health-guards /alarms and alarm actions are ENABLED
- the low pump speed alarm (LPS_alarm) should be active as the pump power is OFF, the pump speed setpoint == 0 rpm, and hence the pump is not running.
- FG ==1 (see Table 3-7), so accumulator flight heater (FAC) will be used.
- Temperature readings will depend on the actual system temperature situation.

4. Tracker normal operating temperature range

The operational temperature range of the Tracker electronics is: -10 ºC to +25 ºC.
The temperatures experienced by the Tracker are the evaporator temperatures, measured by Pt04 and Pt05 at the evaporators' entrances and the Dallas sensors distributed along the evaporator tubing These measured temperatures should be close to the accumulator setpoint and accumulator temperature during steady state operation.

5. Tracker survival temperature range

The survival temperature range of the Tracker electronics is: -20 ºC to +40 ºC.

6. Accumulator normal operating setpoint temperature range

The operational temperature range of the Tracker electronics is: -10 ºC to +25 ºC

The allowed minimum and maximum of the normal operating temperature range of the accumulator setpoint is consistent but not equal to the normal operating temperature range of the Tracker electronics, i.e.: -20 ºC to +25 ºC.
The accumulator temperature is measured by Pt01.
The accumulator temperature should be close to the accumulator setpoint during steady state operation. The accumulator temperature may differ from the accumulator setpoint after a setpoint change, e.g. due to ground command or CAV_alarm action.

7. Pump inlet temperature cavitation margin during normal operation

As the suction pressure at the inlet of a running pump is below the accumulator pressure, the pump inlet liquid temperature must be below the accumulator temperature (= saturation temperature) to prevent CO_2 boiling in the running pump inlet and hence cavitation in the pump. To this end a cavitation margin is to be employed, with default value 5 ºC, i.e. when the pump is running or started, the pump inlet temperature should be at least 5 ºC below the accumulator temperature.
Given the maximum allowed operational temperature of the accumulator, the maximum allowed normal operational temperature of the pump inlet liquid is:
maximum accumulator temp – cavitation margin = 25 – 5 = 20 ºC (default values).
The pump inlet temperature is measured by Pt02.

8. Accumulator setpoint for automatic start-up; + 20 ºC

For an automatic start-up procedure by the JMDC, an accumulator setpoint of 20 ºC is chosen. The rationale is as follows.
The start-up setpoint of the accumulator should be above the pump inlet temperature, measured by Pt02, to prevent cavitation. At start-up the TTCS box has approximately a uniform temperature, which depends on the temperature of the support structure the box is mounted to. The liquid at the pump inlet has a temperature which is slightly below the box temperature, thanks to the small pump radiator.

In order to be able to switch on the pump without the danger of cavitation the accumulator setpoint and actually measured temperature must be above the box temperature.
Therefore automatic start-up an accumulator setpoint of +20 ºC is chosen and a maximum allowed box temperature at start-up of 19 ºC is chosen

A setpoint of +20 ºC is in 90% of the time (but not always) higher than a TTCS box temperature of 19 ºC.

Hence, there remains a risk that during automatic start-up the box temperature (max allowed during automatic start-up is +19 ºC) is close to the start-up setpoint + 20ºC and hence there is only a cavitation margin of 1 ºC.

It has been decided to allow automatic start-up in such a situation. The rationale to allow continuation of automatic start-up in this situation is that the pump can suck in boiling CO_2 for a short time span without harm. Normally, after some time cold liquid from the condensers will enter the pump and boiling -if present- will stop-. Furthermore, the TTCS health-guards are all enabled after TTCE power-up and hence – if this situation occurs- the cavitation margin health-guard will force the accumulator setpoint higher -maximum is +25 ºC- which also alleviates the situation, although the temperature reaction of the accumulator is rather slow.

So, after some time the pump inlet temperature (Pt02) should return well below the accumulator temperature (Pt01). If this does not occur probably there is not enough flow, possibly because the liquid at the pump inlet is boiling.

So, if the Pt02 does not drop a certain margin below the accumulator temperature Pt01 after TBD seconds, the JMDC should stop the pump and signal this situation to the ground.

9. Maximum pump inlet temperature allowed at automatic start-up

As made plausible above the maximum pump inlet temperature allowed at automatic start-up is set to 19ºC.

10. Maximum temporary accumulator setpoint

The used cooling medium CO_2 becomes supercritical above +31ºC. The pump is not designed to handle supercritical CO_2 during extended time periods. So, the pump in cooling loop should not be started-up nor be operational if the accumulator temperature is above +31ºC.

As this temperature is also above the maximum operating temperature of the tracker, an accumulator setpoint above + 25 ºC (but below +31ºC) may only be used temporarily and if the Tracker is NOT ON, e.g. during start-up of the loop, see next.

11. Special situation: manual start-up at high box temperatures: Pt02 between + 19 ºC and +31ºC

In a special situation an accumulator setpoint above + 25 ºC (but below +31ºC) may be required temporarily in order to enable start-up of the pump. E.g. it may be required to start-up the loop in a hot situation where the temperature of the pump inlet (Pt02) in the TTCS box is above + 19 ºC. Taking into account the cavitation margin, the accumulator setpoint in that situation should be above 24 ºC (if possible 5ºC above Pt02, although a smaller margin may be allowed temporarily, but below 31 ºC). After start-up of the pump the cold liquid will cool down the (parts in the) TTCS box, such that after some time the accumulator setpoint may be lowered, to within the operating range of the tracker. A start-up of the pump in this situation is only allowed to be done manually, while monitoring on the ground the various temperatures.

12. Special situation: high box temperatures Pt02 >+31ºC

The loop should not be started-up above these high temperatures.

13. Start-up at low temperatures

CO_2 freezes at approximately -55ºC.

There may be situations that, before the TTCS is started up, the radiators are below-55ºC and the CO_2 in the condensers attached to the radiators are frozen.

The TTCS pumps should not be started-up if there is a danger that the CO_2 in the condensers or condenser feed/return lines is completely or partly frozen.

If the condensers are frozen, first the condenser lines must be heated up before the radiators may be heated up.

So the first logical action after TTCE power-on, is to activate the condenser liquid line heaters control: i.e. enable the 28V LLR and LLW heater power and enable the LLR and LLW on/off control loops. The control loops are on/off control loops. If the condenser liquid lines temperatures are frozen or otherwise below the required temperature, the heaters will be on and ensure defrosting and heating the condenser lines to the desired temperature.

Involved temperatures:

Pt 08a,b, Pt11a,b: at radiator

Pt7a,b, Pt10a,b: at condenser inlet

Pt6a,b, Pt9a,b at condenser lines

All temperatures must be > - 40 ºC (TBD) before pump may be switched on.

On-Off control of LLW and LLR loops

Setpoint range LLW and LLR -32 to +31 ºC

Default setpoint -31 ºC

Sensors used: Pt06 (LLR), Pt09 (LLW)

Control loops are DISABLED at TTCE power-on

The LLW and LLR control loop can function properly even if there is no flow yet, because Pt06 and Pt09 are mounted at the tubes, very close to the heaters.

14. Operation of the radiators health heaters

The operation of the radiators health heaters requires special procedural attention.

Freezing of the radiators can only occur if the PDS does not power the health heaters while the Tracker is not on.

If after TTCE/JMDC power-on Pt07, or Pt06, or Pt10 or Pt09 < -55 ºC there is a danger that the condensers are frozen. In that case first the condenser line health heaters (LLR, LLW) control must be enabled and the condenser lines temperatures Pt07 and Pt10 at the condenser inlets and Pt06 and Pt09 at condenser lines must be > - 40 ºC, before the radiator health heaters may be powered-on by the PDS.

Furthermore, during start-up of a loop, the radiator health heaters must have been powered on and the radiator temperatures Pt 08 and Pt11 must be > - 40 ºC before it can be allowed to start-up the pump.

So in a safe start-up procedure first the condenser health heaters control loops must be enabled and after their temperatures criterion is satisfied, the PDS must power-on the radiator health heaters.

Note.

It remains allowed to power-on the radiators health heaters before the condenser LLR and LLW control loops, under the strict condition that it is clear that the radiators (and hence the condensers) are not frozen (i.e. > -55 ºC).

For example it is allowed to power the radiator health heaters even before a TTCE is powered, provided it is clear that the radiators (and hence the condensers) are not frozen. Doing so, in such a situation the radiator health heaters may prevent freezing of the radiators and condensers.

However, it is emphasized that if the monitored radiator temperatures turn out to be too low (<-55 ºC) immediately after TTCE and JMDC have been powered-on, the condenser lines must be defrosted first, see above and section 8.3.1 TTCS start-up procedure and after the condenser lines temperature satisfy the criteria the radiator health heaters must be powered-on.

15. start-up at normal temperatures

Also at normal temperatures, the first logical action after TTCE power-on, is to activate the condenser liquid line heaters control: i.e. enable the 28V LLR and LLW heater power and enable the LLR and LLW on/off control loops

If the condenser lines temperatures are OK the on/off behaviour of the LLR and LLW control loops will ensure that the heaters are not unnecessarily on.

Furthermore, during start-up of a loop, the radiator health heaters must have been powered on and the radiator temperatures Pt 08 and Pt11 must be > - 40 ºC before it can be allowed to start-up the pump.

Also the accumulator temperature control can be enabled at the same time as the LLR and LLW control is enabled.

All alarms are default ENABLED at power-on.
As pump does not run yet: LPS alarm is active
LPS_alarm active: PR1, PR2, COR, SUP all are OFF, DCV_TEC = 0
So heating accumulator is possible, cooling is not.
LLR and LLW control is possible.

16. Setting of the pre-heaters control loops setpoint

The default setpoint of the pre-heaters specified in Table 3-7 is the delta temperature with respect to the accumulator setpoint.
The absolute pre-heater setpoint is calculated by the TTCE according to:
abs pre-heater setpoint = accu setpoint + pre-heater (delta) setpoint.

During normal operation the CO_2 will enter the pre-heaters approximately at, or slightly below, saturation temperature (is accu setpoint temperature).
In order for the pre-heaters to be switched-on, their control loop setpoints must be above the accumulator setpoint.
The default pre-heater delta setpoint is -4 ºC, see Table 3-7, which implies that the pre-heaters default will be OFF.
As it is required to have the pre-heaters ON during normal operation of the TTCS the pre-heaters control delta setpoints must always be set to the maximum possible positive value allowed by the 6-bit word range (+3.875 ºC).

8.3 TTCS start-up related procedures

Keeping in mind the above know-how and rules, the following start-up related procedures are defined

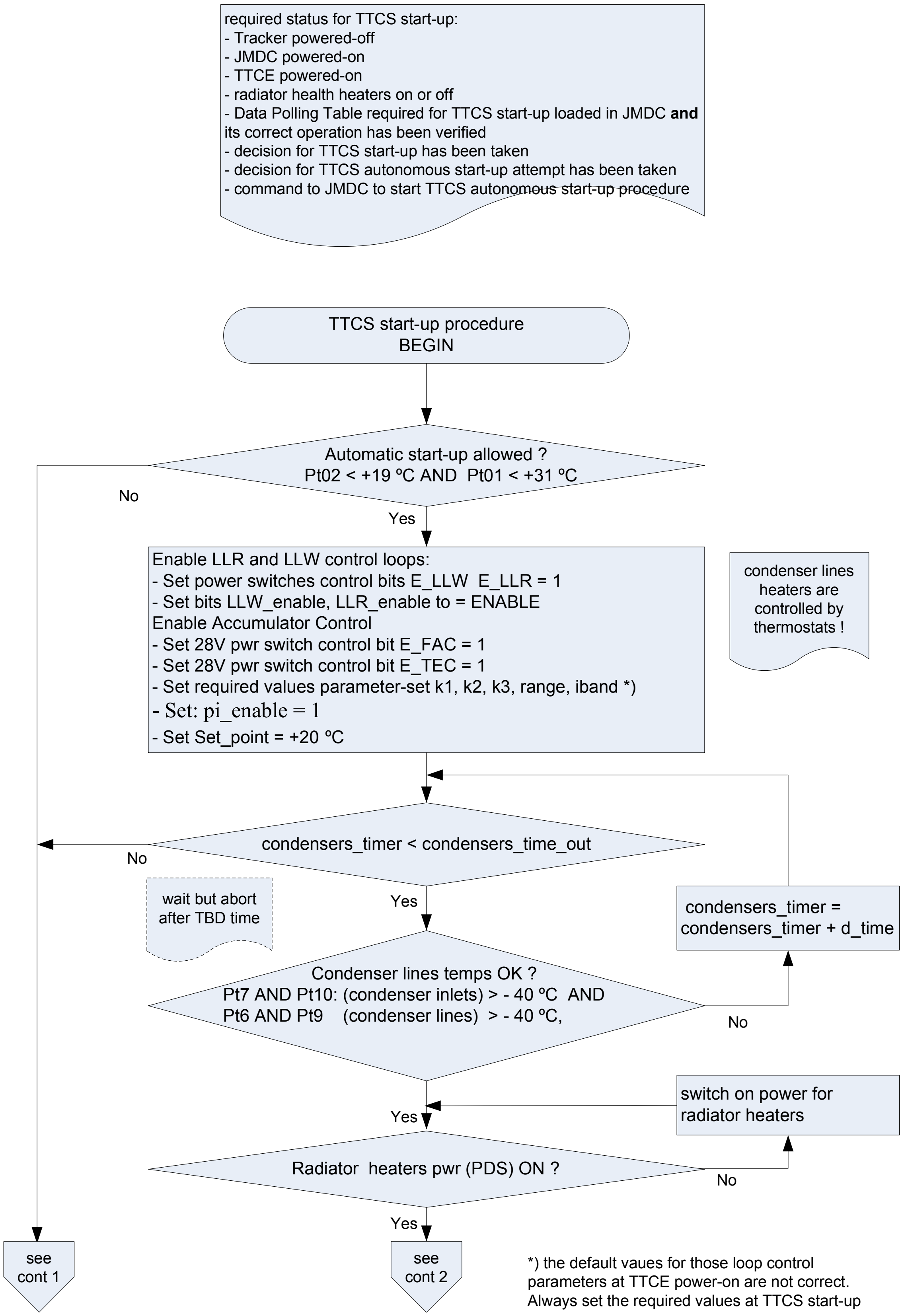
1. TTCS start-up procedure
2. Super saturation prevention after Tracker power-on procedure
3. Accumulator set-point adaptation procedure

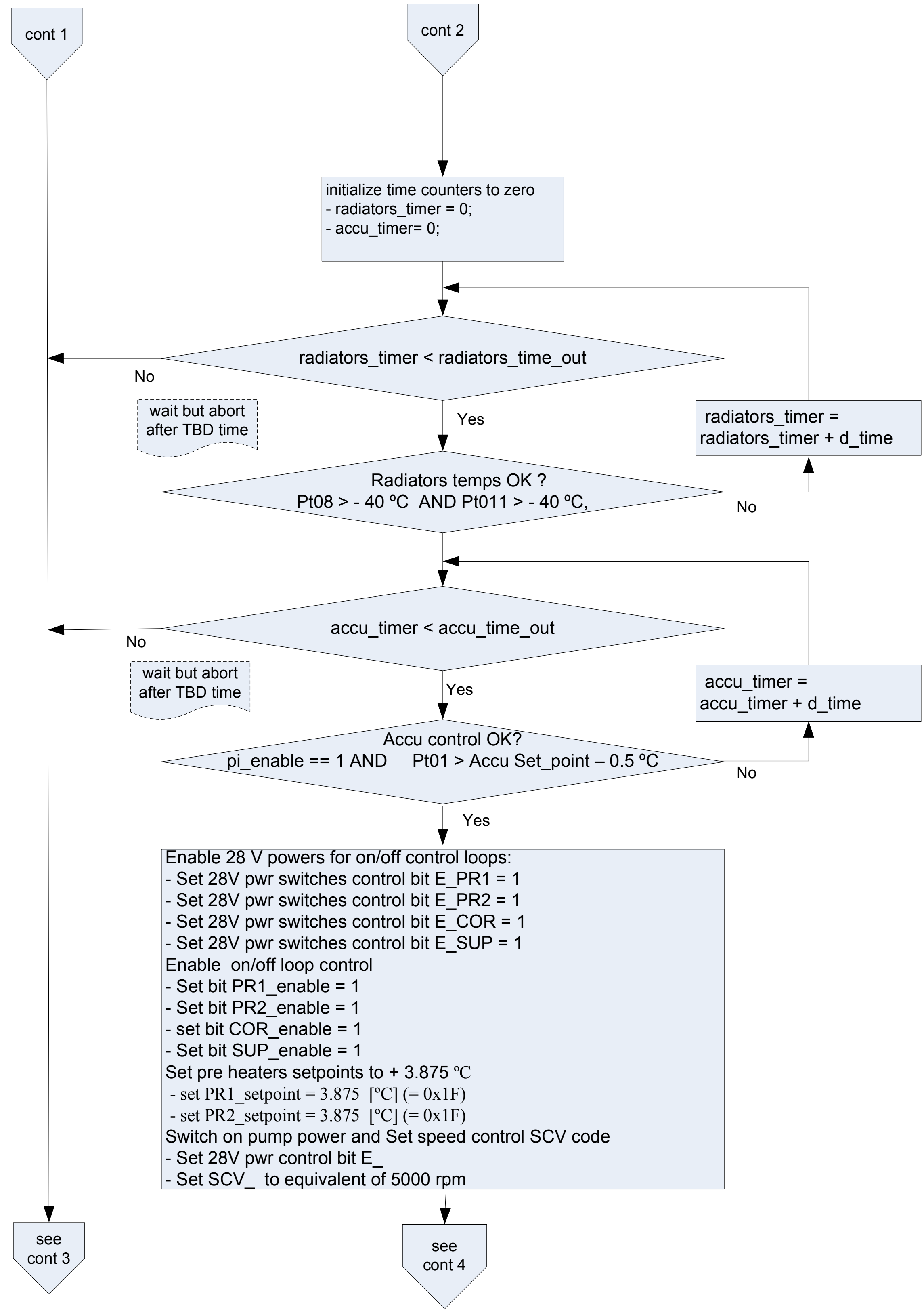
8.3.1 TTCS Start-up procedure

TTCS start-up procedure	
objectives	to start-up a healthy TTCS loop, such that - health-guards are active - 28V supply power is enabled for the used equipment (heaters, pump, TECs) - The correct values for the accumulator control parameters are set - The correct value for the accumulator temperature setpoint is set - The correct values for the pre-heaters setpoint are set - The correct pump speed setpoint is set - The pump is running at the desired speed
commands to be sent	The flow diagram of the start-up procedure is given below in Figure 8-1

parameter	preset value	function/description
condenser_timer	n.a.	timer to check if the condenser lines achieve the desired temperature within reasonable time
condenser_time_out	*)	if the condenser_timer exceeds this value its is judged that the condenser lines heating-up is failing and the TTCS start-up is aborted
radiator_timer	n.a.	timer to check if the radiators achieve the desired temperature within reasonable time
radiator_time_out	*)	if the radiator_timer exceeds this value its is judged that the radiator heating-up is failing and the TTCS start-up is aborted
accu_timer	n.a	timer to check if the accumulator achieves the desired temperature within reasonable time
accu_time_out	*)	if the accu_timer exceeds this value its is judged that the radiator heating-up is failing and the TTCS start-up is aborted
d_time	*)	delta time at which the checks are repeated.
LPS_timer	n.a.	timer to check if the pump speed is above the low pump speed limit within reasonable time
LPS_OK_count	n.a.	counts the time that LPS_alarm = 0 (OFF). Initially the LPS_alarm = 1 (ON). After setting the pump speed setpoint to 5000 rpm, the pump speed should increase from zero, cross the low pump speed alarm limit (2400), and increase further up to

		5000 rpm. After crossing the low pump speed limit the LPS_alarm should be OFF, and the LPS_OK_count will start counting the time that the pump speed is above the low pump speed limit. The pump should be a certain TBD amount of time above the LPS alarm limit, before it can be assumed that the pump speed control is operating correctly.
LPS_OK	180 sec *)	If LPS_OK_count achieves this number within time span LPS_time_out, it is assumed that the pump speed control is operating correctly; else the start-up sequence is to be aborted, see next.
LPS_time_out	600 sec *)	Limit value of LPS_timer. If LPS_OK_count does not achieve LPS_OK within LPS_time_out, it is assumed that the pump speed control does not function correctly and the start-up has to be aborted.
CAV_timer	n.a.	measures the time duration that cavitation danger is present after pump has achieved sufficient speed
CAV_OK_count	n.a.	Number of consecutive times that no cavitation danger is present
CAV_OK	60 sec *)	If CAV_OK_count achieves this number within time span CAV_time_out, it is assumed that cavitation danger during start-up has disappeared; else the start-up has to be aborted, see next.
CAV_time_out	600 sec *)	Limit value of CAV_timer. If CAV_OK_count does not achieve CAV_OK within CAV_time_out, it is assumed that cavitation danger does not disappear as expected and the start-up has to be aborted.
delta_CAV	5 ºC *)	Cavitation margin to be achieved during start-up
*) settable parameter values shall be up-loadable		


required status for TTCS start-up:
- Tracker powered-off
- JMDC powered-on
- TTCE powered-on
- radiator health heaters on or off
- Data Polling Table required for TTCS start-up loaded in JMDC **and** its correct operation has been verified
- decision for TTCS start-up has been taken
- decision for TTCS autonomous start-up attempt has been taken
- command to JMDC to start TTCS autonomous start-up procedure
TTCS start-up procedure BEGIN
Automatic start-up allowed ? Pt02 < +19 ºC AND Pt01 < +31 ºC
No
Yes
Enable LLR and LLW control loops:
- Set power switches control bits E_LLW E_LLR = 1
- Set bits LLW_enable, LLR_enable to = ENABLE
Enable Accumulator Control
- Set 28V pwr switch control bit E_FAC = 1
- Set 28V pwr switch control bit E_TEC = 1
- Set required values parameter-set k1, k2, k3, range, iband *)
- Set: pi_enable = 1
- Set Set_point = +20 ºC
condenser lines heaters are controlled by thermostats !
condensers_timer < condensers_time_out
No
wait but abort after TBD time
Yes
condensers_timer = condensers_timer + d_time
Condenser lines temps OK ?
Pt7 AND Pt10: (condenser inlets) > - 40 ºC AND
Pt6 AND Pt9 (condenser lines) > - 40 ºC,
No
switch on power for radiator heaters
Yes
Radiator heaters pwr (PDS) ON ?
No
Yes
see cont 1
see cont 2
*) the default vaues for those loop control parameters at TTCE power-on are not correct. Always set the required values at TTCS start-up


cont 1
cont 2
initialize time counters to zero
- radiators_timer = 0;
- accu_timer= 0;
radiators_timer < radiators_time_out
No
wait but abort after TBD time
Yes
radiators_timer = radiators_timer + d_time
Radiators temps OK ?
Pt08 > - 40 ºC AND Pt011 > - 40 ºC,
No
accu_timer < accu_time_out
No
wait but abort after TBD time
Yes
accu_timer = accu_timer + d_time
Accu control OK?
pi_enable == 1 AND Pt01 > Accu Set_point – 0.5 ºC
No
Yes
Enable 28 V powers for on/off control loops:
- Set 28V pwr switches control bit E_PR1 = 1
- Set 28V pwr switches control bit E_PR2 = 1
- Set 28V pwr switches control bit E_COR = 1
- Set 28V pwr switches control bit E_SUP = 1
Enable on/off loop control
- Set bit PR1_enable = 1
- Set bit PR2_enable = 1
- set bit COR_enable = 1
- Set bit SUP_enable = 1
Set pre heaters setpoints to + 3.875 ºC
- set PR1_setpoint = 3.875 [ºC] (= 0x1F)
- set PR2_setpoint = 3.875 [ºC] (= 0x1F)
Switch on pump power and Set speed control SCV code
- Set 28V pwr control bit E_
- Set SCV_ to equivalent of 5000 rpm
see cont 3
see cont 4

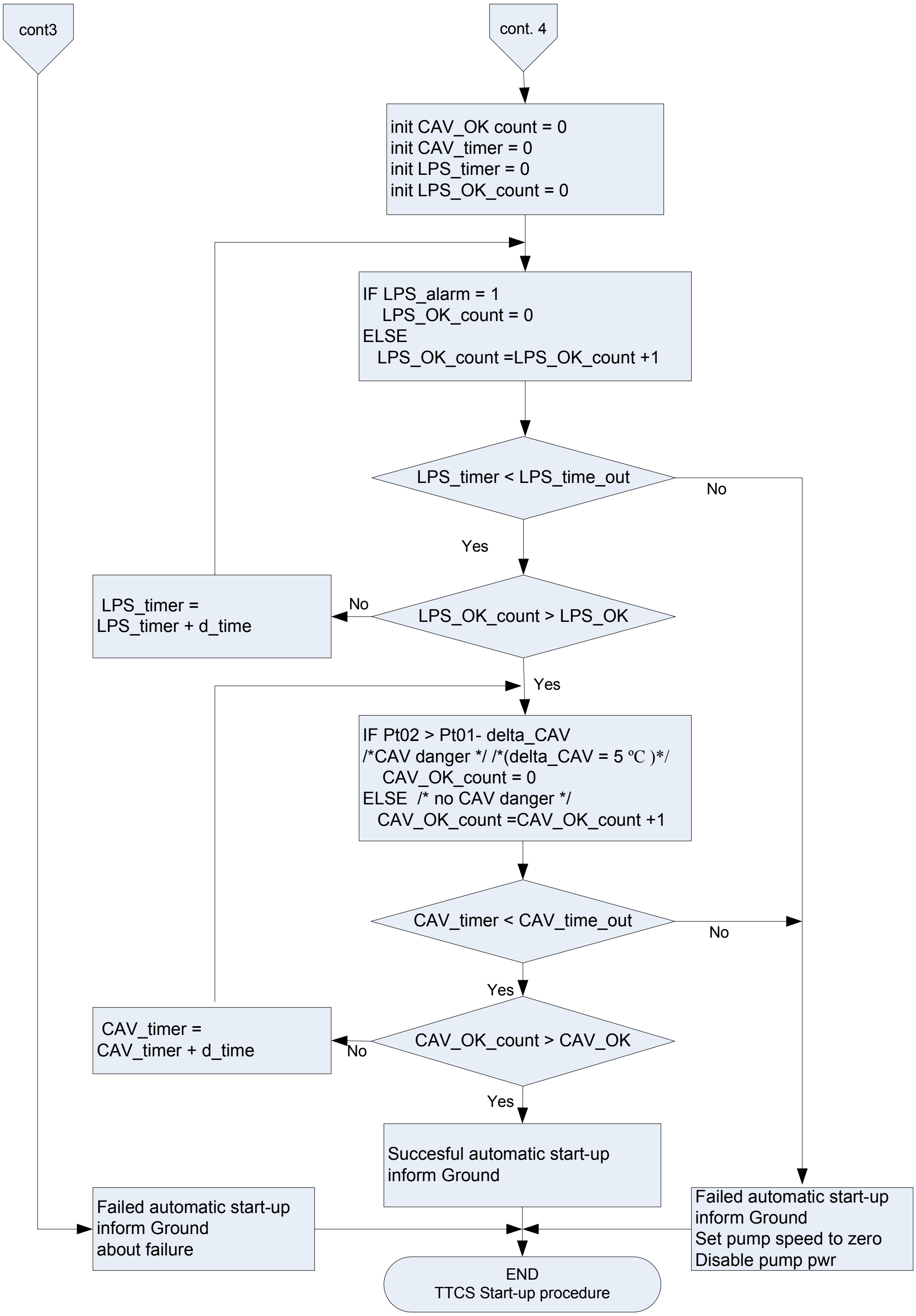

cont3
cont. 4
init CAV_OK count = 0
init CAV_timer = 0
init LPS_timer = 0
init LPS_OK_count = 0
IF LPS_alarm = 1
LPS_OK_count = 0
ELSE
LPS_OK_count =LPS_OK_count +1
LPS_timer < LPS_time_out
No
Yes
LPS_timer =
LPS_timer + d_time
No
LPS_OK_count > LPS_OK
Yes
IF Pt02 > Pt01- delta_CAV
/*CAV danger */ /*(delta_CAV = 5 ºC)*/
CAV_OK_count = 0
ELSE /* no CAV danger */
CAV_OK_count =CAV_OK_count +1
CAV_timer < CAV_time_out
No
Yes
CAV_timer =
CAV_timer + d_time
No
CAV_OK_count > CAV_OK
Yes
Succesful automatic start-up
inform Ground
Failed automatic start-up
inform Ground
about failure
Failed automatic start-up
inform Ground
Set pump speed to zero
Disable pump pwr
END
TTCS Start-up procedure

Figure 8-1 TTCS Start-up procedure flow chart

8.3.2 Super saturation prevention during Tracker start-up

Super saturation prevention after Tracker power-on	
objectives	prevent or cure supersaturating of the cooling liquid after Tracker power-on, by repeatedly switching-on the start-up heaters a number of times (repeat_number), for TBD time (start_up_ON_time, in order to force the onset of boiling. Between the start_up on periods a wait_period is taken into account
commands to be sent	The flow diagram of the procedure is given below in Figure 8-2

parameter	**preset value**	**function/description**
repeat_number	4 *)	the number of times the start-up heaters have to be switched on for the TBD time-span
repeat_count	n.a.	counter of the number of times the start-up heaters have been switched on
wait_period	TBD *)	time period between two consecutive periods of start-up heaters ON
wait_timer		timer to measure if wait period has expired
start_up_ON_time	60sec *)	time span the start-up heater is ON
start-up_time	n.a.	measure the time the start-up heaters is ON
*) settable parameter values shall be up-loadable		

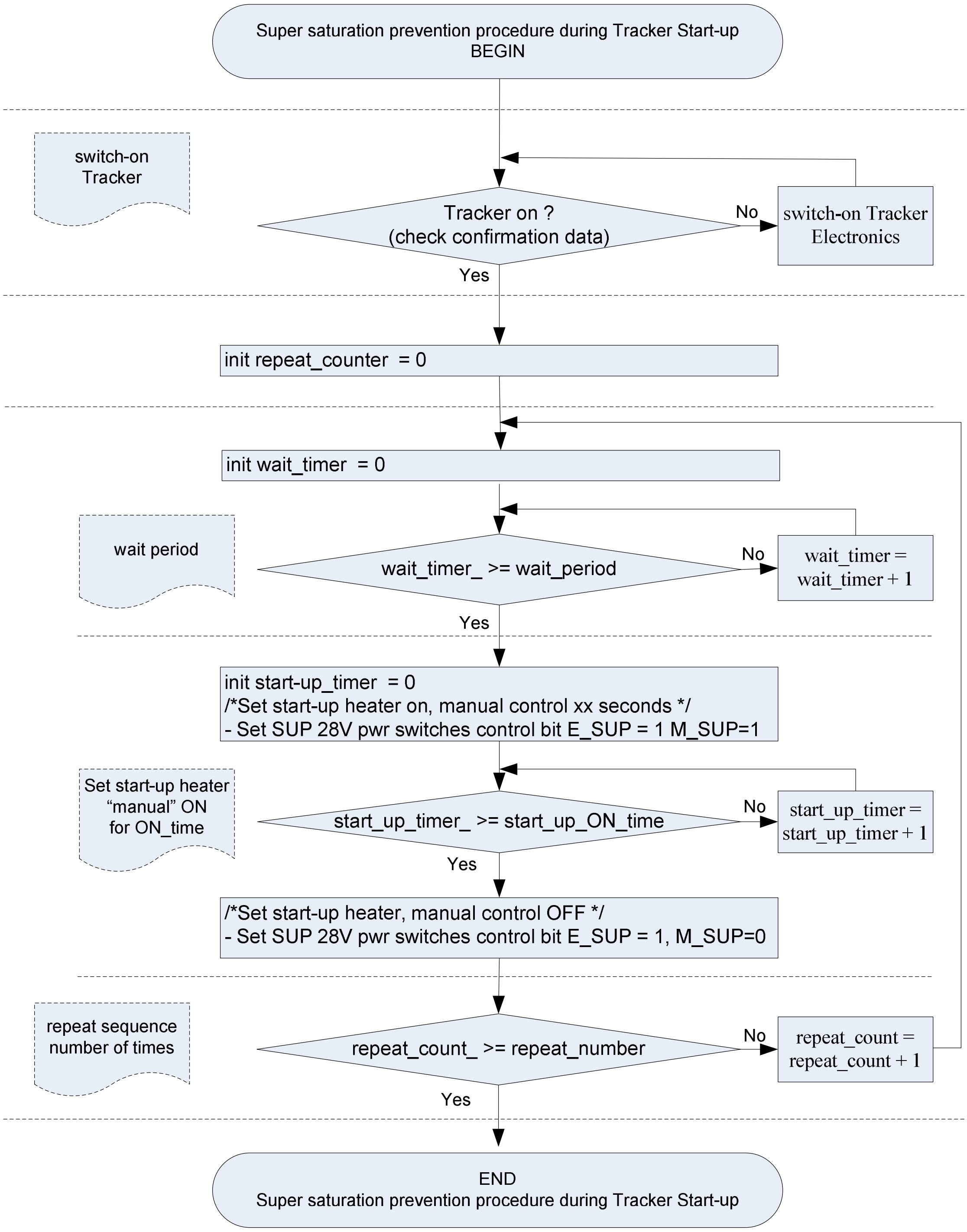
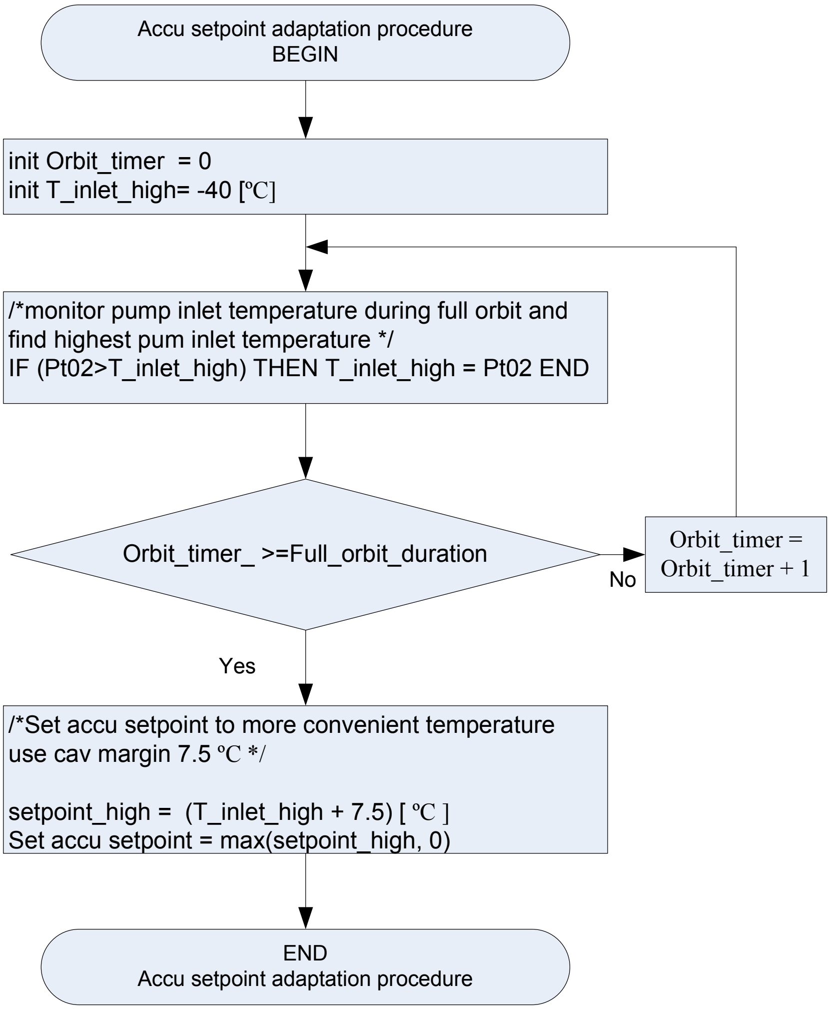


Figure 8-2 Super saturation procedure during Tracker sstart-up

8.4 Accu setpoint adaptation procedure

Accu setpoint optimization procedure	
objectives	The accu temperature setpoint chosen for autonomous start-up may not be optimal, i.e. too high. This procedure is used to autonomously find an optimal accumulator temperature setpoint. The pump inlet temperature is monitored for a full orbit, to find the highest pump inlet temperature which occurred during the orbit The accu setpoint is chosen above the highest pump inlet temperature such that sufficient sub-cooling margin exists. In order to a reliable value, noisy EMC induced errors in the Prt02 readings must be filtered and spikes and outliers must be rejected. The maximum rate of change of the actual pump inlet temperature in-flight is estimated 1 ºC per minute, which may be used for filtering.
commands to be sent	The flow diagram of the procedure is given below in

parameter	**preset value**	**function/description**
full_orbit_duration	5400 sec *)	full orbit duration
orbit_timer	n.a.	measured time since start of procedure
T_inlet_high	-40 ºC. *)	highest pump inlet temperature measured. -40 ºC is initialization value.
cav_margin	7.5 ºC *)	cavitation/sub-cooling margin. It is noted that during most parts of the orbit the actual sub-cooling will be larger
setpoint_high	n.a.	adapted accu setpoint
*) settable parameter values shall be up-loadable		


Accu setpoint adaptation procedure
BEGIN
init Orbit_timer = 0
init T_inlet_high= -40 [ºC]
/*monitor pump inlet temperature during full orbit and
find highest pum inlet temperature */
IF (Pt02>T_inlet_high) THEN T_inlet_high = Pt02 END
Orbit_timer_ >=Full_orbit_duration
No
Orbit_timer =
Orbit_timer + 1
Yes
/*Set accu setpoint to more convenient temperature
use cav margin 7.5 ºC */
setpoint_high = (T_inlet_high + 7.5) [ºC]
Set accu setpoint = max(setpoint_high, 0)
END
Accu setpoint adaptation procedure

8.5 TTCS monitoring and failure detection

TBW ?

Appendix I: Overview of Read data type definitions

Data type nr	action request	Description
0x19	Read Pt1000	Request Data: None Reply: 44 bytes, 2x11 Prime Loop, 2x11 Secondary Loop Temperatures Two byte per T First byte = signed char, temperature in ℃ Second byte: 4 LSbits = 1/16℃, bit 5 & bit4 Redund ancy Control (RC), bit7 & bit6 Vote Result (VR) RC = 00->0(N), 01->1(L), 10->2(R), 11->Vote VR = 00->0(N), 01->1(L), 10->2(R), 11->Illegal T[℃] = First byte + (Second byte & 0x0F)/16.0 Order of T values in reply: T names second byte Bits: 7,6 5,4 Pt01_P VR RC Pt02_P VR RC Pt03_P VR RC Pt04_P VR RC Pt05_P VR RC Pt06_P 00 00 Pt07_P 00 00 Pt08_P 00 00 Pt09_P 00 00 Pt10_P 00 00 Pt11_P 00 00 Pt01_S VR RC Pt02_S VR RC Pt03_S VR RC Pt04_S VR RC P0t5_S VR RC Pt06_S 00 00 Pt07_S 00 00 Pt08_S 00 00 Pt09_S 00 00 Pt10_S 00 00 Pt11_S 00 00
0x1A	Read APS/DPS	Request Data: None Reply: 8 bytes, APS_P, DPS_P, APS_S, DPS_S Two byte per pressure sensor First byte = 8 MSbits Second byte: bit3 & bit2 & bit1 & bit0 = 4LSbits
0x07	Read 28V	Request Data: None Reply: 5 bytes with values of Control bits for each switch: Switch Control bit name byte & bit E_LLW_P 0 0 E_LLR_P 0 1 E_PR1_P 0 2 E_PR2_P 0 3 E_COR_P 0 4 E_SUP_P 0 5 E_GAE_P 0 6 E_FAE_P 0 7 M_LLW_P 1 0 M_LLR_P 1 1 M_PR1_P 1 2 M_PR2_P 1 3 M_COR_P 1 4 M_SUP_P 1 5 M_GAE_P 1 6 M_FAE_P 1 7 E_LLW_S 2 0

		E_LLR_S 2 1 E_PR1_S 2 2 E_PR2_S 2 3 E_COR_S 2 4 E_SUP_S 2 5 E_GAE_S 2 6 E_FAE_S 2 7 M_LLW_S 3 0 M_LLR_S 3 1 M_PR1_S 3 2 M_PR2_S 3 3 M_COR_S 3 4 M_SUP_S 3 5 M_GAE_S 3 6 M_FAE_S 3 7 E_GAC_P 4 0 E_FAC_P 4 1 E_TEC_P 4 2 E_GAC_S 4 3 E_FAC_S 4 4 E_TEC_S 4 5 P_P 4 6 P_S 4 7
0x08	Read Pump	Request Data: None Reply: 6 bytes Byte SCV_P 0 SCV_S 1 PPS_P 8MSbits 2 PPS_P 4LSbits 3 (bit3 & bit2 & bit1 & bit0) PPS_S 8MSbits 4 PPS_S 4LSbits 5 (bit3 & bit2 & bit1 & bit0) SCV - Speed Control Voltage PPS ñ Pulse per second Pump speed (RPM) = PPS / 9.0 * 60.0
0x09	Read PWM	Request Data: None Reply: 6 byte Byte DCV_GAC_P 0 DCV_FAC_P 1 DCV_TEC_P 2 DCV_GAC_S 3 DCV_FAC_S 4 DCV_TEC_S 5
0x0A	Read Loop ctrl	Request Data: None Reply: 64 bytes One byte per parameter Read only bit/bytes marked RO Read and Clear bits marked RC Parameters for Primary Loop (0 – x1F) x00 Control bits5-4:range, 3:heat RO, 2:FG, 1:test, 0:pi_enable x01 Set_point bits5-0: accumulator set point (-32℃ - 31℃) x02 k1 Unsigned 8-bit, LSbit = 1 (0 - 255) x03 k2 Unsigned 8-bit, LSbit = 1/16 (0 - 15.9375) x04 k3 Unsigned 8-bit, LSbit = 1 (0 - 255) x05 iband Unsigned 6-bit, LSbit = 1/16℃ (0 – 3.9375℃) x06 Feed_forw MSB, Signed 16-bit (-32768 – 32767) x07 Feed_forw LSB x08 Test_T 4MSbits=0, bits3-0 contain bits 11-8 of Test_T x09 Test_T bits7-0 of Test_T, LSbit = 1/16℃ (-128℃ – +127.9375℃) x0A ph_term RO MSB, signed 16-bit x0B ph_term RO LSB x0C ih_term RO MSB, signed 16-bit x0D ih_term RO LSB x0E pi_dcv RO Unsigned char

		x0F cav_margine bits4-0, LSbit = 1/2℃ (0 - 15.5 ℃) x10 LLW_Loop bit7:out RO, 6:enable, 5-0:set point (-32℃ - 31℃) x11 LLR_Loop bit7:out RO, 6:enable, 5-0:set point (-32℃ - 31℃) x12 PR1_Loop bit7:out RO, 6:enable, 5-0:set point (-4℃ - 3.875℃) x13 PR2_Loop bit7:out RO, 6:enable, 5-0:set point (-4℃ - 3.875℃) x14 COR_Loop bit7:out RO, 6:enable, 5-0:set point (-32℃ - 31℃) x15 SUP_Loop bit7:out RO, 6:enable, 5-0:set point (-32℃ - 31℃) x16 alarm_ena 7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV x17 alarm_now RO all 7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV x18 alarm_was RC all 7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV x19 cycle_cnt RC number of temperature measurement cycles after last read x1A Not defined RO x1B Not defined RO x1C Not defined RO x1D Not defined RO x1E Not defined RO x1F Not defined RO x20 - x3F set of the same parameters for Secondary Loop
0x17	Write DS ID Table	Request Data: one byte Bus Number, 8 x NDS bytes – DS IDs Reply: Done *)
0x16	Write DS Control Reg.	Request Data: one byte, four DS Bus Enable LSbits Reply: Done
0x18	Read DS Temp.	Request Data: one byte, only 2 LSbits, Bus Number Reply: one byte Bus Number, 2 x NDS Temperature Two byte per DS First byte = signed char, temperature in ℃ Second byte: MSbit = 0 -> T is valid, MSbit = 1 -> Error, 4 LSbits = T in 1/16 of ℃ If Second byte MSbit = 0 then T[℃] = First byte + Second byte/16.0

*) To be verified and better discussed. The approach for now is to write explicitly which ID read and then read. Is this the best option?

Appendix II: TTCE Embedded Firmware Code

```
                                TTCE_Data_Type4.txt
File TTCE_Data_Type4.txt
11 June   2008
Corretions were made to TTCE_Data_Type3.txt (6 Febrary 2008 FM/FS ):

1.      now:    x05 iband         Unsigned 6-bit, LSbit = 1/16'C (0 - 3.9375'C)
        was:    x05 iband         Unsigned 8-bit, LSbit = 1/16'C (0 - 3.9375'C)

2.      now:    x04 k3            Unsigned 8-bit, LSbit = 1 (0 - 255)
        was:    x04 k3            Unsigned 8-bit, LSbit = 1/32  (0 - 7.96875)

TTEC-A has logical address 6C, TTEC-B has logical address 6D

Data Types:

  1.      x01     Read    Ping
  2.      x05     Write   Start Erase Flash Sector
  3.      x05     Read    Erase Status (NOT IMPLEMENTED)
  4.      x06     Read    Memory
  5.      x06     Write   Memory
  6.      x15     Write   Start DS Scan
  7.      x15     Read    DS Scan Status
  8.      x16     Read    DS Control Register
  9.      x16     Write   DS Control Register
 10.      x17     Read    DS ID Table
 11.      x17     Write   DS ID Table
 12.      x18     Read    DS Temperatures
 13.      x19     Read    Pt1000 Temperatures
 14.      x19     Write   Pt1000 Redundancy Control
 15.      x1A     Read    Pressure Sensors
 16.      x07     Write   28V Control
 17.      x07     Read    28V Control
 18.      x08     Write   Pump Control
 19.      x08     Read    Pump Control
 20.      x09     Write   PWM Control
 21.      x09     Read    PWM Control
 22.      x03     Write   Execute Configuration File
 23.      x1B     Write   Delay 10 msec
 24.      x0A     Write   Loop Control
 25.      x0A     Read    Loop Control


  1.    x01     Read    Ping
                        Request Data:  Length 0 - 8191 bytes
                        Reply: Length 0 - 8191 bytes, the same Data as in the
Request

  2.    x05     Write   Start Erase Flash Sector
                        Request Data: Sector Number (0x0 - 0xF), one byte, only
four LSbits used
                        Reply: Done if flash erase was started, abort if in
Configuration file


  3.    x05     Read    Erase Status NOT IMPLEMENTED

                        Status of the erase sector number N operation can be
found
                        reading memory at address 0x1N0000. The erase sector
operation
                        has been completed if two consecutive reading data were
equal.

  4.    x06     Read    Memory
                        Request Data: Bcnt1, Bcnt0, Addr2, Addr1, Addr0
                        Bcnt1 & Bcnt0 - Number of bytes to be read can be 0-8187
                        Addr2 & Addr1 & Addr0 - 21 bits memory start address
                        Reply: Bcnt1, Bcnt0, Addr2, Addr1, Addr0, memory data
```

```
                         TTCE_Data_Type4.txt
  5.     x06      Write   Memory
                          Request Data: Bcnt1, Bcnt0, Addr2, Addr1, Addr0
                          Bcnt1 & Bcnt0 - Number of bytes to be written, can be
0-8186
                          Addr2 & Addr1 & Addr0 - 21 bits memory start address
                          Reply: Done if success, else Abort

  6.     x15      Write   Start DS Scan
                          Request Data: one byte, bit3->DS Bus3, bit2->DS Bus2,
                          bit1->DS Bus1, bit0->DS Bus0
                          Reply: Done

  7.     x15      Read    DS Scan Status
                          Request Data: None
                          Reply: Status in four LSbits, NDS0, NDS1, NDS2, and NDS3
                          NDSx - number of Dallas Sensors found at Bus x

  8.     x16      Read    DS Control Register
                          Request Data: None
                          Reply: one byte, four LSbits with DS Bus Enable

  9.     x16      Write   DS Control Register
                          Request Data: one byte, four DS Bus Enable LSbits
                          Reply: Done

10.      x17      Read    DS ID Table
                          Request Data: one byte, only 2 LSbits, Bus Number
                          Reply: one byte Bus Number, 8 x NDS bytes - DS IDs
                          NDS - number of Dallas Sensors


11.      x17      Write   DS ID Table
                          Request Data: one byte Bus Number, 8 x NDS bytes - DS
IDs
                          Reply: Done

12.      x18      Read    DS Temperatures
                          Request Data:  one byte, only 2 LSbits, Bus Number
                          Reply: one byte Bus Number, 2 x NDS Temperature
                          Two byte per DS
                          First byte = signed char, temperature in °C
                          Second byte: MSbit = 0 -> T is valid, MSbit = 1 ->
Error,
                          4 LSbits = T in 1/16 of °C
                          If Second byte MSbit = 0 then T[°C] = First byte +
Second byte/16.0

13.      x19      Read    Pt1000 Temperatures
                          Request Data:  None
                          Reply: 44 bytes, 2x11 Prime Loop, 2x11 Secondary Loop
Temperatures
                          Two byte per T
                          First byte = signed char, temperature in °C
                          Second byte: 4 LSbits = 1/16°C, bit 5 & bit4 Redundancy
Control (RC),
                          bit7 & bit6 Vote Result (VR)
                          RC = 00->0(N), 01->1(L), 10->2(R), 11->Vote
                          VR = 00->0(N), 01->1(L), 10->2(R), 11->Illegal
                          T[°C] = First byte + (Second byte & 0x0F)/16.0
                          Order of T values in reply:
                          T names           second byte
                                  Bits: 7,6      5,4
                          Pt01_P            VR       RC
                          Pt02_P            VR       RC
                          Pt03_P            VR       RC
                          Pt04_P            VR       RC
                          Pt05_P            VR       RC
                          Pt06_P            00       00
                                      Page 2
```

```
        TTCE_Data_Type4.txt
Pt07_P          00      00
Pt08_P          00      00
Pt09_P          00      00
Pt10_P          00      00
Pt11_P          00      00
Pt01_S          VR      RC
Pt02_S          VR      RC
Pt03_S          VR      RC
Pt04_S          VR      RC
P0t5_S          VR      RC
Pt06_S          00      00
Pt07_S          00      00
Pt08_S          00      00
Pt09_S          00      00
Pt10_S          00      00
Pt11_S          00      00

There are all Pt1000 readouts (ADC) in SRAM starting
from address 0x050000
To read ALL Pt1000 sensors, data type Read Memory should
be used.
Pt1000 readout (ADC) is 12 bits in two bytes:
First byte = 0000 & 4 MSbits
Second byte = LSB
REF0, REF1, REF2 - Precision resistor readout
corresponding T=0'C
T['C] = (Pt1000 readout - REF readout)/16.0
REF0 is reference for sensor i at address 0x050000 + 6*i
REF1 is reference for sensor i at address 0x050000 + 6*i
+ 2
REF2 is reference for sensor i at address 0x050000 + 6*i
+ 4
where i from 1 to 23
NC - Not Connected to PT1000
PtNNZP(S): NN - sensor number, Z = 0, 1, 2 (or N, L, R)
redundant sensors
                                   Z = _ not redundant
sensors

REF0    0x050000      REF1    0x050002      REF2
0x050004
Pt010P  0x050006      Pt011P  0x050008      Pt012P
0x05000A
Pt020P  0x05000C      Pt021P  0x05000E      Pt022P
0x050010
Pt030P  0x050012      Pt031P  0x050014      Pt032P
0x050016
Pt040P  0x050018      Pt041P  0x05001A      Pt042P
0x05001C
Pt050P  0x05001E      Pt051P  0x050020      Pt052P
0x050022
Pt06_P  0x050024      Pt07_P  0x050026      Pt08_P
0x050028
Pt09_P  0x05002A      Pt10_P  0x05002C      Pt11_P
0x05002E

NC      0x050030      NC      0x050032      NC
0x050034
Pt010S  0x050036      Pt011S  0x050038      Pt012S
0x05003A
Pt020S  0x05003C      Pt021S  0x05003E      Pt022S
0x050040
Pt030S  0x050042      Pt031S  0x050044      Pt032S
0x050046
Pt040S  0x050048      Pt041S  0x05004A      Pt042S
0x05004C
Pt050S  0x05004E      Pt051S  0x050050      Pt052S
0x050052
                 Page 3
```

```
                                TTCE_Data_Type4.txt
                          Pt06_S   0x050054          Pt07_S   0x050056          Pt08_S
0x050058
                          Pt09_S   0x05005A          Pt10_S   0x05005C          Pt11_S
0x05005E

                          NC       0x050060          NC       0x050062          NC
0x050064
                          NC       0x050066          NC       0x050068          NC
0x05006A
                          NC       0x05006C          NC       0x05006E          NC
0x050070
                          NC       0x050072          NC       0x050074          NC
0x050076
                          NC       0x050078          NC       0x05007A          NC
0x05007C
                          NC       0x05007E          NC       0x050080          NC
0x050082
                          NC       0x050084          NC       0x050086          NC
0x050088
                          NC       0x05008A          NC       0x05008C          NC
0x05008E

14.       x19      Write  Pt1000 Redundancy Control
                          Request Data:  One byte per Redundant Temperature
Measurement Point
                          Reply: Done
                          Can be from 1 to 10 Data bytes
                          bit3 & bit2 & bit1 & bit0 =address, 0_9 valid
                          bit5 & bit4 = 00->0(N), 01->1(L), 10->2(R), 11-Vote

15.       x1A      Read   Pressure Sensors
                          Request Data:  None
                          Reply: 8 bytes, APS_P, DPS_P, APS_S, DPS_S
                          Two byte per pressure sensor
                          First byte = 8 MSbits
                          Second byte: bit3 & bit2 & bit1 & bit0 = 4LSbits

16.       x07      Write  28V Control
                          Request Data: 8 bytes
                          Reply: Done
                          There are 16 different heaters each powered by 28V
through two
                          switches (E, M) connected in series.
                          There is control bit for each switch. Control bit = 0 -
switch is OFF,
                          control bit = 1 - switch is ON.
                          Control bit can be set according rule:
                          If (Write Enable bit == 1) then Control bit = Set value

                          Switch      Set value    Write Enable bit
                          name         byte & bit      byte & bit
                          E_LLW_P        0   0           2   0
                          E_LLR_P        0   1           2   1
                          E_PR1_P        0   2           2   2
                          E_PR2_P        0   3           2   3
                          E_COR_P        0   4           2   4
                          E_SUP_P        0   5           2   5
                          E_GAE_P        0   6           2   6
                          E_FAE_P        0   7           2   7

                          M_LLW_P        1   0           2   0
                          M_LLR_P        1   1           2   1
                          M_PR1_P        1   2           2   2
                          M_PR2_P        1   3           2   3
                          M_COR_P        1   4           2   4
                          M_SUP_P        1   5           2   5
                                    Page 4
```

```
          TTCE_Data_Type4.txt
M_GAE_P                1   6            2   6
M_FAE_P                1   7            2   7

E_LLW_S                3   0            5   0
E_LLR_S                3   1            5   1
E_PR1_S                3   2            5   2
E_PR2_S                3   3            5   3
E_COR_S                3   4            5   4
E_SUP_S                3   5            5   5
E_GAE_S                3   6            5   6
E_FAE_S                3   7            5   7

M_LLW_S                4   0            5   0
M_LLR_S                4   1            5   1
M_PR1_S                4   2            5   2
M_PR2_S                4   3            5   3
M_COR_S                4   4            5   4
M_SUP_S                4   5            5   5
M_GAE_S                4   6            5   6
M_FAE_S                4   7            5   7

There are 6 regulated voltage (PWM) loads powered by 28V
through
one switch each and 2 pump 28V switches :

Switch        Set value     Write Enable bit
name           byte & bit       byte & bit
E_GAC_P                6   0            7   0
E_FAC_P                6   1            7   1
E_TEC_P                6   2            7   2
E_GAC_S                6   3            7   3
E_FAC_S                6   4            7   4
E_TEC_S                6   5            7   5
P_P                    6   6            7   6
P_S                    6   7            7   7

17.     x07     Read     28V Control
                         Request Data:   None
                         Reply: 5 bytes with values of Control bits for each
switch:

Switch        Control bit
name           byte & bit
E_LLW_P                0   0
E_LLR_P                0   1
E_PR1_P                0   2
E_PR2_P                0   3
E_COR_P                0   4
E_SUP_P                0   5
E_GAE_P                0   6
E_FAE_P                0   7

M_LLW_P                1   0
M_LLR_P                1   1
M_PR1_P                1   2
M_PR2_P                1   3
M_COR_P                1   4
M_SUP_P                1   5
M_GAE_P                1   6
M_FAE_P                1   7

E_LLW_S                2   0
E_LLR_S                2   1
E_PR1_S                2   2
E_PR2_S                2   3
E_COR_S                2   4
E_SUP_S                2   5
                   Page 5
```

TTCE_Data_Type4.txt

```
E_GAE_S         2   6
E_FAE_S         2   7

M_LLW_S         3   0
M_LLR_S         3   1
M_PR1_S         3   2
M_PR2_S         3   3
M_COR_S         3   4
M_SUP_S         3   5
M_GAE_S         3   6
M_FAE_S         3   7

E_GAC_P         4   0
E_FAC_P         4   1
E_TEC_P         4   2
E_GAC_S         4   3
E_FAC_S         4   4
E_TEC_S         4   5
P_P             4   6
P_S             4   7
```

```
18.    x08    Write    Pump Control
                       Request Data: 2 byte
                       Reply: Done
                       Byte 0  SCV_P   Speed Control Voltage for Pump in Prime
Loop
                       Byte 1  SCV_S   Speed Control Voltage for Pump in
Secondary Loop
                       Control Voltage V = 4096 * (SCV Code / 256) [mV]

19.    x08    Read     Pump Control
                       Request Data: None
                       Reply: 6 bytes
                                       Byte
                       SCV_P           0
                       SCV_S           1
                       PPS_P   8MSbits 2
                       PPS_P   4LSbits 3 (bit3 & bit2 & bit1 & bit0)
                       PPS_S   8MSbits 4
                       PPS_S   4LSbits 5 (bit3 & bit2 & bit1 & bit0)

                       SCV - Speed Control Voltage
                       PPS - Pulse per second
                       Pump speed (RPM) = PPS / 9.0 * 60.0

20.    x09    Write    PWM Control
                       Request Data: from 2 to 12 byte
                       Reply: Done
                       Two bytes per PWM controller
                       Byte0 - Address (0..5 valid)
                       Byte1 - DCV Duty Cycle Value
                       PWM controller output is 0V (OFF) if DCV=0
                       Duty Cycle 99.6% if DCV=255
                                       Address
                       DCV_GAC_P       0
                       DCV_FAC_P       1
                       DCV_TEC_P       2
                       DCV_GAC_S       3
                       DCV_FAC_S       4
                       DCV_TEC_S       5

21.    x09    Read     PWM Control
                       Request Data: None
                       Reply: 6 byte
                                       Byte
```

```
                        TTCE_Data_Type4.txt
                     DCV_GAC_P        0
                     DCV_FAC_P        1
                     DCV_TEC_P        2
                     DCV_GAC_S        3
                     DCV_FAC_S        4
                     DCV_TEC_S        5
22.      x03    Write    Execute Configuration File
                     Request Data: None
                     Reply: Done if Configuration file execution complete,
                     Abort if Configuration file check sum test error or
recursive execution
                     The Log file contains execution details.

                Configuration file should be written into flash memory starting
from address 0x100000
                (it is flash sector #0).

                Configuration file format:

                     Request length MSB              // first request

                     Request length LSB
                     Request Data Type
                     Request Data
                     ...
                     Request length MSB              // last request
                     Request length LSB
                     Request Data Type
                     Request Data
                     0x00                            // zero length
                     0x00
                     CKS MSB                         // Configuration file
Check Sum
                     CKS LSB

                Log file format (in memory starting from 0x040000):

                     Request length MSB              // first executed
request
                     Request length LSB
                     Request Data Type
                     Request Data
                     Status                          // request execution
status
                     ...
                     Request length MSB              // last executed request
                     Request length LSB
                     Request Data Type
                     Request Data
                     Status                          // request execution
status
                     0x00
                     0x00

                     Status = 0 if request done, status = 1 if request abort

                Configuration file is executed when:
                     1. TTCE was OFF and power (28V) is applied to TTCE
                     2. TTCE receives Execute Configuration file request
(0x03)

                Configuration file execution actions:

                // Check Sum test. CKS is unsigned 16-bit, memory( ) is unsigned
char
```

```
                                  TTCE_Data_Type4.txt
                              address = 0x100000;
                              CKS = 0;
                          a:  CKS = CKS + memory(address) + memory(address + 1);
                              length = 256 * memory(address) + memory(address + 1);
                              address = address + 2;
                              if (length != 0 & address < 0x1040000) {
                                for (i=0; i<length; i++; address++) CKS = CKS +
memory(address);
                                goto a;
                              }
                              If (address >= 0x1040000) abort;
                              If (CKS != 256 * memory(address) + memory(address + 1))
{
                                abort;
                              }
                      // Execution
                              address = 0x100000;
                              log_addr = 0x040000;
                          b:  length = 256 * memory(address) + memory(address + 1);
                              if (length != 0 & address < 0x1040000) {
                                memory(log_addr) = memory(address);    // copy request
length to log
                                memory(log_addr + 1) = memory (address + 1);
                                log_addr = log_addr + 2;
                                address = address + 2;
                                request = address;
                                for (i=0; i<length; i++; log_addr++; address++) //copy
request to log
                                  memory(log_addr) = memory(address);
                                result = EXECUTE(length, request, WRITE); //force
abort for READ request
                                If (result == abort) memory(log_addr) = 1; else
memory(log_addr) = 0;
                                log_addr = log_addr + 1;
                                goto b;
                              }
                              done;

23.      x1B     write    Delay 10 msec
                          Request Data: None
                          Reply: Done after 10 msecond
                          Can be used in configuration file to provide delay
between operations

24.      x0A     Write    Loop Control
                          Request Data: from 2 to 128 bytes
                          Reply: Done
                          Two bytes per parameter
                          Byte0 - Address (0...63 valid)
                          Byte1 - Parameter Value

25.      x0A     Read     Loop Control
                          Request Data: None
                          Reply: 64 bytes
                          One byte per parameter
                          Read only bit/bytes marked RO
                          Read and Clear bits marked RC

                      Parameters for Primary Loop (0 - x1F)

                      x00 Control       bits5-4:range, 3:heat RO, 2:FG, 1:test,
0:pi_enable
                      x01 Set_point     bits5-0: accumulator set point (-32°C -
31°C)
                                       Page 8
```

```
                               TTCE_Data_Type4.txt
                     x02 k1               Unsigned 8-bit, LSbit = 1 (0 - 255)
                     x03 k2               Unsigned 8-bit, LSbit = 1/16 (0 -
15.9375)
                     x04 k3               Unsigned 8-bit, LSbit = 1 (0 - 255)
                     x05 iband            Unsigned 6-bit, LSbit = 1/16°C (0 -
3.9375°C)
                     x06 Feed_forw        MSB, Signed 16-bit (-32768 - 32767)
                     x07 Feed_forw        LSB
                     x08 Test_T           4MSbits=0, bits3-0 contain bits 11-8 of
Test_T
                     x09 Test_T           bits7-0 of Test_T, LSbit = 1/16°C
(-128°C - +127.9375°C)
                     x0A ph_term          RO MSB, signed 16-bit
                     x0B ph_term          RO LSB
                     x0C ih_term          RO MSB, signed 16-bit
                     x0D ih_term          RO LSB
                     x0E pi_dcv           RO Unsigned char
                     x0F cav_magine       bits4-0, LSbit = 1/2°C (0 - 15.5°C)
                     x10 LLW_Loop         bit7:out RO, 6:enable, 5-0:set point
(-32°C - 31°C)
                     x11 LLR_Loop         bit7:out RO, 6:enable, 5-0:set point
(-32°C - 31°C)
                     x12 PR1_Loop         bit7:out RO, 6:enable, 5-0:set point
(-4°C - 3.875°C)
                     x13 PR2_Loop         bit7:out RO, 6:enable, 5-0:set point
(-4°C - 3.875°C)
                     x14 COR_Loop         bit7:out RO, 6:enable, 5-0:set point
(-32°C - 31°C)
                     x15 SUP_Loop         bit7:out RO, 6:enable, 5-0:set point
(-32°C - 31°C)
                     x16 alarm_ena               7:GAC, 6:LPS, 5:LLR, 4:LLW,
3:PR2, 2:PR1, 1:TRK, 0:CAV
                     x17 alarm_now        RO all 7:GAC, 6:LPS, 5:LLR, 4:LLW,
3:PR2, 2:PR1, 1:TRK, 0:CAV
                     x18 alarm_was        RC all 7:GAC, 6:LPS, 5:LLR, 4:LLW,
3:PR2, 2:PR1, 1:TRK, 0:CAV
                     x19 cycle_cnt        RC number of tmperature measurement
cycles after last read
                     x1A Not defined      RO
                     x1B Not defined      RO
                     x1C Not defined      RO
                     x1D Not defined      RO
                     x1E Not defined      RO
                     x1F Not defined      RO

                      x20 - x3F set of the same parameters for Secondary Loop

                     Power-On default values for Loop Control:

                     x00 Control          range=0, FG=1, test=0, pi_enable=0
                     x01 Set_point        0°C
                     x02 k1               16       16
                     x03 k2               0x10     1.0
                     x04 k3               0x10     0.5
                     x05 iband            0x10     1°C
                     x06 Feed_forw        0
                     x07 Feed_forw        0
                     x08 Test_T           0        0.0°C
                     x09 Test_T           0
                     x0A ph_term          depend on Pt01_P
                     x0B ph_term          depend on Pt01_P
                     x0C ih_term          0
                     x0D ih_term          0
                     x0E pi_dcv           depend on Pt01_P
                     x0F cav_margin       0x0A     5°C
                     x10 LLW_Loop         0x20   -31°C, enable=0, out=0
                     x11 LLR_Loop         0x20   -31°C, enable=0, out=0
                                    Page 9
```

```
                 TTCE_Data_Type4.txt
x12 PR1_Loop        0x20   -4°C, enable=0, out=0
x13 PR1_Loop        0x20   -4°C, enable=0, out=0
x14 COR_Loop        0x20  -31°C, enable=0, out=0
x15 SUP_Loop        0x20  -31°C, enable=0, out=0
x16 alarm_ena       0xFF  All alarms are enabled
x17 alarm_now       depend on Pt01_P - Pt09_P
x18 alarm_was       depend on Pt01_P - Pt09_P
x19 cycle_cnt       # of cycles after power-on (modulo 256)
x1A Not defined     0
x1B Not defined     0
x1C Not defined     0
x1D Not defined     0
x1E Not defined     0
x1F Not defined     0

                      x20 - x3F set of the corresponding parameters for
Secondary Loop

        Loop Control parameters are the settings and monitoring values which
provide
        automatic control over:

        1. Accumulator Heaters and Peltiers
        2. Liquid Line Health Heaters
        3. Preheaters
        4. Cold Orbit Heaters
        5. Start-up Heaters
        6. Alarms (health guards)

        TTCE measures temperatures and evaluates new settings for PWM and ON/OFF
control
        every cycle = 0.786432 seconds.

        Primary Loop Parameters x00-x0E (x20-x2E for Secondary Loop) are used in
Accumulator
        temperature PI regulation.

        Primary Loop Parameters x10-x15 (x30-x35 for Secondary Loop) are used in
ON/OFF
        loop control for Liquid Line Health Heaters (LLW & LLR), Preheaters (PR1
& PR2),
        Cold Orbit Heater (COR), Start-up Heater (SUP).

        Primary Loop Parameters x0F, x16-x18 (x2F, x36-x38 for Secondary Loop)
are used
        for Alarms control.

        Parameters Definitions:

        pi_enable      if pi_enable = 1 then pi_dcv is used for
Accumulator/Peltier PWM
                       control else DCV_GAC, DCV_FAC, DCV_TEC are used.

        test           if test = 1 then Test Temperature value is substituted
instead
                       of measured temperature Pt01.

        FG             if FG = 1 then Flight Accumulator Control (FAC) Heater
                       will be used else Ground Testing  Accumulator Control
(GAC)
                       Heater will be used.

        heat           if heat = 1 then Accumulator Control (FAC or GAC) Heater
will
                       be used else Peltier will be used.

        range          P-term lineare range (0: ±3.9375°C, 2: ±1.9375°C , 1:
                                  Page 10
```

TTCE_Data_Type4.txt

```
±0.9375°C)
        Set_point     accumulator set point, bits5-0, LSbit=1°C (-32°C - +31°C)

        k1            proportional term coefficient (0 - 255)

        k2            integral term coefficient, LSbit=1/16 (0 - 15.9375)

        k3            peltier coefficient, LSbit=1/32 (0 - 7.96875)

        iband         If the temperature is in the range Set_point ± iband
                      and pi_enable=1 then the error is integrated else
                      i_term = 0. LSbit = 1/16°C (0 - 3.9375°C).

        Feed_forw     constant term to compensate known heat leak (-32768 -
32767)

        Test_T        the temperature which is used in test mode (test=1)
                      signed 12-bit, LSbit = 1/16°C (-128°C - +127.9375°C),

        ph_term       proportional term divided by two, ph_term = p_temt/2
                      signed 16-bit (-32768 - 32767)

        ih_term       integral term divided by two, ih_term = i_temt/2
                      signed 16-bit (-32768 - 32767),

        pi_dcv        duty cycle value which is used for PWM control of
                      Accumulator Heater (0-240, heat=1) or
                      Peltier (0-127, heat=0) if pi_enable=1

        cav_margin    Minimum allowable differance between Accumulator Set_point
and
                      Pump inlet temperature (Pt02). There is cavitation alarm
(CAV) if
                      Set_point < Pt02 + cav_margin

        LLW_enable    enable Liquid Line WAK heater (LLW) loop control

        LLW_set_point LLW loop conrol set point (-32°C - 31°C)

        LLW_out       LLW loop control output,
                      if (LLW_set_point > Pt09) LLW_out = 1; else LLW_out = 0;
                      If LLW_out = 1 and LLW loop is anabled (LLW_enable = 1)
and
                      there is no active LLW alarm (LLW_alarm_act = 0) and there
is no
                      active Cavitation alarm (CAV_alarm_act = 0) then LLW
heater is ON.

        LLR_enable    enable Liquid Line RAM heater (LLR) loop control

        LLR_set_point LLR loop conrol set point (-32°C - 31°C)

        LLR_out       LLR loop control output,
                      if (LLR_set_point > Pt06) LLR_out = 1; else LLR_out = 0;
                      If LLR_out = 1 and LLR loop is anabled (LLR_enable = 1)
and
                      there is no active LLR alarm (LLR_alarm_act = 0) and there
is no
                      active Cavitation alarm (CAV_alarm_act = 0) then LLR
heater is ON.

        PR1_enable    enable Preheater 1 (PR1) loop control

        PR1_set_point PR1 loop conrol set point (-4°C - 3.875°C)
```

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```
                         TTCE_Data_Type4.txt
        PR1_out         PR1 loop control output,
                        if (Set_point + PR1_set_point > Pt04) PR1_out = 1; else
PR1_out = 0;
                        If PR1_out = 1 and PR1 loop is anabled (PR1_enable = 1)
and
                        there is no active PR1 alarm (PR1_alarm_act = 0) and there
is no
                        active Cavitation alarm (CAV_alarm_act = 0) and there is
no active
                        Low Pump Speed alarm (LPS_alarm_act = 0) then PR1 heater
is ON.
        PR2_enable      enable Preheater 2 (PR2) loop control
        PR2_set_point   PR2 loop conrol set point (-4°C - 3.875°C)
        PR2_out         PR2 loop control output,
                        if (Set_point + PR2_set_point > Pt05) PR2_out = 1; else
PR2_out = 0;
                        If PR2_out = 1 and PR2 loop is anabled (PR2_enable = 1)
and
                        there is no active PR2 alarm (PR2_alarm_act = 0) and there
is no
                        active Cavitation alarm (CAV_alarm_act = 0) and there is
no active
                        Low Pump Speed alarm (LPS_alarm_act = 0) then PR2 heater
is ON.
        COR_enable      enable Cold Orbit heater (COR) loop control
        COR_set_point   COR loop conrol set point (-32°C - 31°C)
        COR_out         COR loop control output,
                        if (COR_set_point > Pt02) COR_out = 1; else COR_out = 0;
                        If COR_out = 1 and COR loop is anabled (COR_enable = 1)
and
                        there is no active Cavitation alarm (CAV_alarm_act = 0)
and
                        there is no active Low Pump Speed alarm (LPS_alarm_act =
0)then
                        COR heater is ON.

        SUP_enable      enable Start Up heater (SUP) loop control
        SUP_set_point   SUP loop conrol set point (-32°C - 31°C)
        SUP_out         SUP loop control output,
                        if (SUP_set_point > Pt04) SUP_out = 1; else SUP_out = 0;
                        If SUP_out = 1 and SUP loop is anabled (SUP_enable = 1)
and
                        there is no active Cavitation alarm (CAV_alarm_act = 0)
and
                        there is no active Low Pump Speed alarm (LPS_alarm_act =
0)then
                        SUP heater is ON.
        CAV_alarm_ena   Cavitation alarm enable
        TRK_alarm_ena   Trecker alarm enable
        PR1_alarm_ena   Preheater 1 alarm enable
        PR2_alarm_ena   Preheater 2 alarm enable
        LLW_alarm_ena   Liquid Line WAK heater alarm enable
        LLR_alarm_ena   Liquid Line RAM heater alarm enable
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        LPS_alarm_ena Low Pump speed (LPS) alarm enable

        GAC_alarm_ena Ground Test Accumulator Control heater (GAC) alarm enable

        CAV_alarm_now Cavitation alarm now is 1 if Set_point < Pt02 + cav_margin
else 0

        TRK_alarm_now Trecker alarm now is 1 if Pt04,Pt05 < -20°C or Pt04,Pt05 >
20°C else 0

        PR1_alarm_now Preheater 1 alarm now is 1 if Pt04 > 35°C else 0

        PR2_alarm_now Preheater 2 alarm now is 1 if Pt05 > 35°C else 0

        LLW_alarm_now Liquid Line WAK heater alarm now is 1 if Pt09 > 35°C else
0

        LLR_alarm_now Liquid Line RAM heater alarm now is 1 if Pt06 > 35°C else
0

        LPS_alarm_now Low Pump speed (LPS) alarm now is 1 if Pump Speed < 2400
rpm else 0

        GAC_alarm_now Ground Test Accumulator Control heater (GAC) alarm now
                      is 1 if Pt03 > 45°C else 0

        XXX_alarm_was XXX = CAV, TRK, PR1, PR2, LLW, LLR, LPS, GAC
                      XXX_alarm_was is set to 1 if XXX_alarm_now = 1
                      XXX_alarm_was is set to 0 when Read Loop Control (x0A) is
executed
                      Read Loop Control is READ and CLEAR operation for
XXX_alarm_was

        cycle_cnt     cycle counter is incremeting every cycle (0.786432sec)

                      cycle_cnt is set to 0 when Read Loop Control (x0A) is
executed
                      Read Loop Control is READ and CLEAR operation for
cycle_cnt

        Alarms definitions:

        if (Set_point < Pt02 + cav_margin) CAV_alarm_now = 1; else CAV_alarm_now
= 0;
        if (Pt04 >  20°C || Pt05 >  20°C ||
            Pt04 < -20°C || Pt05 < -20°C ) TRK_alarm_now = 1; else TRK_alarm_now
= 0;
        if (Pt04 > 35°C)                   PR1_alarm_now = 1; else PR1_alarm_now
= 0;
        if (Pt05 > 35°C)                   PR2_alarm_now = 1; else PR2_alarm_now
= 0;
        if (Pt09 > 35°C)                   LLW_alarm_now = 1; else LLW_alarm_now
= 0;
        if (Pt06 > 35°C)                   LLR_alarm_now = 1; else LLR_alarm_now
= 0;
        if (Pump Speed < 2400rpm)          LSP_alarm_now = 1; else LSP_alarm_now
= 0;
        if (Pt03 > 45°C)                   GAC_alarm_now = 1; else GAC_alarm_now
= 0;

        Alarms actions:

        if (XXX_alarm_now == 1 && XXX_alarm_ena == 1) XXX_alarm_act = 1; else
XXX_alarm_act = 0;
```

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```
        if (CAV_alarm_act == 1 && Set_point < 25°C) Set_point_now = MIN(Pt02 +
cav_magin, 25°C); else
                                            Set_point_now = Set_point;
        if (CAV_alarm_act == 1) {LLW OFF; LLR OFF; PR1 OFF; PR2 OFF; COR OFF;
SUP OFF;}
        if (TRK_alarm_act == 1) ;
        if (PR1_alarm_act == 1) PR1 OFF;
        if (PR2_alarm_act == 1) PR2 OFF;
        if (LLW_alarm_act == 1) LLW OFF;
        if (LLR_alarm_act == 1) LLR OFF;
        if (LSP_alarm_act == 1) {PR1 OFF; PR2 OFF; COR OFF; SUP OFF; TEC_DCV=0;}

        if (GAC_alarm_act == 1) GAC OFF;


        ON/OFF loop control formulas (executed every cycle = 0.786432 seconds):

        if (                LLW_set_point > Pt09) LLW_out = 1; else LLW_out = 0;
        if (                LLR_set_point > Pt06) LLR_out = 1; else LLR_out = 0;
        if (Set_point_now + PR1_set_point > Pt04) PR1_out = 1; else PR1_out = 0;
        if (Set_point_now + PR2_set_point > Pt05) PR2_out = 1; else PR2_out = 0;
        if (                COR_set_point > Pt02) COR_out = 1; else COR_out = 0;
        if (                SUP_set_point > Pt04) SUP_out = 1; else SUP_out = 0;

        Accumulator PI regulation formulas (executed every cycle = 0.786432
seconds):

        error_T = Set_point_now - measured_T;  // LSbit = 1/16°C, (±3.9375°C)

        abs_error_T = ABS(error_T);  // (0 - 3.9375°C)

        if (abs_error_T < iband) in_iband = 1; else in_iband = 0;

        if      (error_T > 0.9375°C && range == 1) {error_T = 0.9375°C; big_p_err
= 1;}
        elseif (error_T <-0.9375°C && range == 1) {error_T =-0.9375°C; big_n_err
= 1;}
        elseif (error_T > 1.9375°C && range == 2) {error_T = 1.9375°C; big_p_err
= 1;}
        elseif (error_T <-1.9375°C && range == 2) {error_T =-1.9375°C; big_n_err
= 1;}
        elseif (error_T > 3.9375°C)               {error_T = 3.9375°C; big_p_err
= 1;}
        elseif (error_T <-3.9375°C)               {error_T =-3.9375°C; big_n_err
= 1;}
        else {big_p_err = 0; big_n_err = 0;}

        p_term = 4 * R * K1 * error_T; //(±64260), R=4 if range=1, R=2 if
range=2, else R=1

        if (in_iband = 1 & enable = 1)
                i_term = i_term + k2/16 * error_T; else i_term = 0; // (±65535)

        pi_val = p_term + i_term + Feed_forw; // (±65535)

        if (pi_val >= 0) heat = 1; pi_abs = pi_val; else heat = 0; pi_abs =
-pi_val;

        pi_tec = k3/32/256 * pi_abs; // (0 - 2047)

        pi_heat = SQRT(pi_abs);   // (0 - 255)  sqrt to compensate fact that P ~
U * U

        if (pi_tec > 127 || big_n_err == 1) pi_tec = 127; // Limit to 13.7V
```

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```
        if (pi_heat > 240 || big_p_err == 1) pi_heat = 240; // PWM works
unstable if DC > 95%

        if (heat == 1) pi_dcv = pi_heat; else pi_dcv = pi_tec;
```

END OF DOCUMENT